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ASSESSMENT OF BIOREMEDIATION TECHNOLOGIES: FOCUS ON TECHNOLOGIES SUITABLE FOR FIELD-LEVEL DEMONSTRATIONS AND APPLICABLE TO DoD CONTAMINANTS

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Office of the Deputy Under Secretary of Defense
Environmental Security

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PREFACE

This work was performed for the Deputy Undersecretary of Defense, Environmental Security under the task, "Strategic Planning and Analytical Support for the DoD Environmental Cleanup Program." This work represents partial fulfillment of the requirements of the task order.

We would like to express our gratitude to the following reviewers who provided perceptive and valuable comments on an earlier draft:

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We chose, after careful consideration, not to implement a few of their comments. We hope that we have incorporated the spirit of many of their comments. Any inaccuracies in the document should be viewed as the sole responsibility of the authors.

Felicia Brady of the IDA library staff provided timely and cheerful assistance in obtaining many of the references required for this work and to her we are indebted. Finally, we would like to express our appreciation to the Task Leader, Dr. Phillip Gould, for his support over the duration of this project.

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EXECUTIVE SUMMARY

Bioremediation is a viable, cost-effective treatment for environmental contaminants. Research activities continue to uncover new bioremediation technologies, increasing the need for field-level demonstrations. The goal of this study is to identify bioremediation technologies that have demonstrated viability in laboratory or pilot studies, but require additional field demonstrations to determine the capabilities and limitations of the technology. Our intent is to assess the state of the art in biological techniques for the remediation of contaminants common to the Department of Defense. Therefore, we concentrate on emerging and laboratory scale treatments that are likely to benefit from field tests. Technologies that have been demonstrated under field conditions and are available at commercial scales are discussed only briefly. Examples of such technologies include bioventing for the treatment of light hydrocarbons in soils and composting for the treatment of energetics. These technologies have been applied at many sites, and as a result have gained acceptance in the environmental community as competitive alternatives to conventional chemical and physical treatments.

In selecting technologies that would be of interest to the DoD, the Service-identified research and development priorities for cleanup were considered, and those contaminants amenable to bioremediation were identified. These contaminants included halogenated and non-halogenated hydrocarbons, energetics, and inorganics.[1] The various technologies, from those in their infancy to those currently used at commercial scales, for bioremediation of these contaminants were considered. These technologies were readily separated into three groups: (1) those that have been demonstrated and are already used at commercial scales, (2) those that are so immature that field demonstrations would be unlikely to produce useful results, and (3) those that are promising at either laboratory or pilot scales and are in need of demonstrations for validation under field conditions. The latter group, the group of interest, has only four members: bioreactors for the treatment of energetics, *in situ* anaerobic/aerobic sequential treatment of chlorinated hydrocarbons, constructed

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1 Some biological activities are capable of changing the mobility or solubility of inorganic substances. Thus, we include inorganics in the category of contaminants that are amenable to bioremediation.

wetlands, and white rot fungus. We strongly recommend the first three technologies as candidates for field-level demonstrations; the fourth we recommend less enthusiastically.

Bioreactors for treatment of energetics. Bioreactors can be of either the lagoon type, where the contaminants are left in a lagoon to which nutrients and water are added to enhance microbial activity, or the above-ground type, where groundwater or excavated soil mixed with water is enclosed in a surface construction. Treatments using lagoon-type bioreactors should be undertaken with caution until the mechanisms of degradation are well understood and controls are well established. In either lagoons or above-ground reactors, the contaminated material is mixed with nutrients and oxygen, and maintained as a suspension in the reactor. Bioreactors have been applied to sludges and groundwater contaminated with energetics, petroleum hydrocarbons, petrochemicals, solvents, pesticides, wood preservatives, and other organic chemicals with varying degrees of success. Treatment of energetics can be either aerobic or anaerobic, and treatment times can be short, on the order of days. Demonstrations have been limited to laboratory and pilot scale, with problems still to be solved before the technology can be brought to full scale.

In situ anaerobic/aerobic sequential treatment of chlorinated hydrocarbons. For highly chlorinated organic contamination, anaerobic reductive dehalogenation followed by aerobic degradation has been demonstrated in *ex situ* bioreactors. Routine procedures for implementing this sequence *in situ* have not yet been established at the commercial scale. Obstacles to implementing this technology for *in situ* use include the difficulty of transporting electron donors and acceptors to the contaminant, transporting a primary substrate to the microorganisms, and attaining complete mineralization. The prevalence of chlorinated solvent contamination and the expense of alternative pump-and-treat methods make this technology worthy of development.

Constructed wetlands. Constructed wetlands contain robust consortia of living organisms that involve higher plant species as well as microbes. Constructed wetlands have the ability to treat a variety of contaminants simultaneously. Constructed wetlands have been demonstrated at the pilot scale, and a full scale demonstration is planned under the EPA Superfund Innovative Technology Evaluation (SITE) program. If the time scale of these tests is favorable, the results should be examined closely to determine if further demonstrations are warranted. Engineering of optimal conditions may require additional field trials.

White rot fungus. The ability of white rot fungus to treat some contaminants has been known for 10–15 years. White rot fungus has successfully degraded TNT (2,4,6-

trinitrotoluene) in pure aqueous cultures in many laboratory and pilot scale tests. In addition, the results of laboratory and pilot scale demonstrations have shown the potential for white rot fungus to degrade not only nitroaromatics (TNT) and nitramines (RDX and HMX), but also other difficult to degrade materials such as DDT, PAHs, PCBs and PCP. Nevertheless, there are a number of obstacles that limit the use of this technology at the commercial scale. These include competition from native bacteria, toxicity of contaminants to the fungus, chemical sorption, and engineering the fungal treatment to meet desired cleanup levels. Further, for all applications, questions remain about the ultimate fate of the contaminants and intermediates. In the many years of testing on white rot fungal systems, field-level experiments have failed to acheive the performance demonstrated in the laboratory. Thus, we recommend that any proposed field-level demonstration that utilizes white rot fungus be examined for evidence of scientific or engineering breakthroughs that might improve the likelihood of success at the field scale. In light of the ability of white rot fungus to degrade many refractory contaminants, we are reluctant to dismiss it entirely; however, without significant improvements in the process, a field-scale demonstration using white rot fungus is likely to fail.

Beyond our primary recommendations, we make note of two other technologies of interest: microbial mats and systems capable of assessing and monitoring bioremediation activities.

Microbial mats. Microbial mats, like constructed wetlands, contain complex consortia of aerobic and anaerobic bacteria that have shown the potential to treat a variety of contaminants, including energetics, heavy metals and polycyclic aromatic hydrocarbons. Laboratory demonstrations have shown greater than 99 percent depletion of energetics from an initial concentration of 100 ppm in a matter of days. Treatment of metals using microbial mats is less mature, but controlled experiments have shown decreases in metal concentrations of 80–90 percent from initial concentrations that would be toxic to many microbial systems. The ultimate fate of contaminants, particularly metals that are isolated rather than mineralized, the implications of adsorption rather than degradation of contaminants, and the creation of intermediates are issues that must be addressed before the technology can be brought to full scale. Although demonstrations of microbial mat treatments have been limited to the laboratory, the potential for treating a variety of contaminants simultaneously may justify investment in larger demonstrations. However, investment in this less mature technology at the full-scale level carries a high risk of failure. Therefore, additional testing at the pilot scale is encouraged.

Evaluation and monitoring technologies. Many bioremediation technologies suffer from the lack of adequate systems for evaluating and monitoring relevant parameters. As such, it is often difficult to determine whether the biological system is responsible for the contaminant degradation or containment. The development of systems for use in monitoring or assessing the status of biological treatment processes is needed for all bioremediation applications. This need is particularly acute if intrinsic bioremediation is to be advanced as a treatment alternative.

I. GOAL OF THE STUDY

Bioremediation is a viable, cost-effective treatment for environmental contaminants. Research activities continue to uncover new bioremediation technologies, increasing the need for field-level demonstrations. The goal of this study is to identify bioremediation technologies that have demonstrated viability in laboratory or pilot studies, but require additional field demonstrations to identify the capabilities and limitations of the technology. Our intent is to assess the state of the art in biological techniques for the remediation of contaminants common to the Department of Defense. Therefore, we concentrate on emerging and laboratory scale treatments that are likely to benefit from field tests. Technologies that have been demonstrated under field conditions and are available at commercial scales are discussed only briefly. Examples of such technologies include bioventing for the treatment of light hydrocarbons in soils and composting for the treatment of energetics. These technologies have been applied at many sites, and as a result have gained acceptance in the environmental community as competitive alternatives to conventional chemical and physical treatments.

II. BASICS OF BIOREMEDIATION

Bioremediation makes use of the ability of organisms (primarily bacteria, fungi, and algae) to transform hazardous contaminants into innocuous substances. In some cases, bioremediation does not transform the contaminants, but rather immobilizes them. In these latter cases, bioremediation can be used to contain the contamination either indefinitely or until other chemical or physical treatments can be used.[1] Biodegradation is not new. It is inherent in the life cycle of the planet; microorganisms are responsible for transforming human, animal, and plant wastes into reusable products. The oil industry has harnessed biodegradation as a tool since the 1920's to extend the production of oil wells; microorganisms that produce emulsifiers or surfactants are used to recover additional oil after wells have stopped flowing. Microorganisms have also long been used in municipal wastewater treatment. These same biological capabilities have more recently been exploited for the bioremediation of contaminants in the environment.

Microorganisms degrade contaminants by producing enzymes that catalyze reactions. For treatment to take place, enzyme production in microbial systems must first be induced. This requires a "food" source, which provides energy (in the form of electrons) and carbon (the core building material for new cells). With energy and carbon, microbes are able to grow and reproduce.

In environmental bioremediation, organic contaminants often serve as the "food" source. Some carbon from the organic contaminant is used for cell growth, and the remainder is converted to CO_2 in the degradation process. Where the contaminant cannot be used by the microorganism as a primary food source, a supplemental food source is required. Energy for cell growth is obtained from the flow of electrons associated with oxidation-reduction (redox) reactions. There are many redox reactions available to microbial systems. The microbe will couple the redox reactions that produce the highest energy yield. In most cases, the organic contaminant serves as the electron donor (i.e., it is oxidized), and the electrons are transferred to an electron acceptor. In the case of aerobic

1 The use of bioremediation to stabilize a site is an area of growing interest. Stabilization has the potential to be a valuable tool in the cleanup of sites or in the reduction of risk.

biodegradation, the terminal electron acceptor is oxygen. In most bioremediation processes, the supply of the electron acceptor or oxidant is the predominant factor limiting the ability of microbial systems to thrive and perform the desired degradation reactions. Table 1 summarizes the basic requirements of microbial systems.

Table 1. Basic Requirements of Microbial Bioremediation Systems (Ref. 1)

- Microbes - a diverse population for survivability and thorough degradation.
- Energy and carbon source.
- Inducer to cause synthesis of enzymes for destruction of the target compound; for example, some fungi, bacteria or algae will produce the desired enzymes only in a nitrogen-deficient environment.
- Electron acceptor/donor system.
- Appropriate environmental conditions—moisture, pH, absence of microbial toxins, and temperature (for every 10 °C increase in temperature up to 55 °C, the biodegradation rate constant is approximately doubled).
- Nutrients to support cell growth and enzyme production—a typical cell consists of approximately 50 percent carbon, 14 percent nitrogen, 3 percent phosphorus, 2 percent potassium, 1 percent sulfur, 0.2 percent iron, and 0.5 percent calcium, magnesium, and chloride. All must be present; however, biodegradation appears to be limited by the availability of electron acceptors, e.g., oxygen, rather than trace nutrients.
- Presence of organisms to degrade the metabolic products—a diverse microbial population may contain such organisms.

For bioremediation processes to be successful, the basic conditions of microbial (or fungal) systems must be met; however, it is often the engineering aspects of the process that limit feasibility, cost effectiveness, and hence applicability. For example, it may be impractical to transport nutrients to the microbial system, or it may be cost-prohibitive to control the temperature of the system. There has been a great deal of effort devoted to understanding the biochemistry of the organisms—the determination of detailed degradation pathways, the production of intermediates, and the factors that limit enzyme production. However, often there has been insufficient focus on the engineering aspects of bioremediation. As a result, many bioremediation technologies have languished in the laboratory.

Depending on the contaminant, the matrix, and other environmental conditions, bioremediation can take place in a number of ways. It can be naturally occurring (intrinsic) requiring no intervention, or it may require engineering in the form of nutrient delivery, fluid circulation, or temperature control. Bioremediation biochemically transforms the contaminants, which either reduces their toxicity or changes their mobility. Descriptions of

the various biological means of transformation and mobility change appear below. The end products listed are those that ideally would be obtained if the contaminants were completely degraded, i.e., the organic contaminants are mineralized to form carbon dioxide and water. This complete degradation is not always achieved, as toxic and refractory intermediates are often produced as well.

Classes of bioremediation that transform contaminants:[2]

1. Aerobic bioremediation: microbes use oxygen as the terminal electron acceptor.

   Principal end products: CO_2, H_2O, increased cell population, products of incomplete destruction.

2. Anaerobic bioremediation: microbes use an electron acceptor other than oxygen (nitrate, NO_3^-; sulfate, SO_4^{2-}; carbon dioxide, CO_2; or a metal such as iron, Fe^{3+}; and manganese, Mn^{4+}).

   Principal end products: nitrogen gas, hydrogen sulfide, reduced forms of metals, methane, increased cell population, products of incomplete destruction.

3. Facultative organism bioremediation: microbes are able to function in aerobic or anaerobic conditions.

4. Fermentation: microbes use organic material as both the electron donor and the electron acceptor.

   Principal end products: fermentation products such as acetate, propionate, ethanol, hydrogen, and CO_2. These can be further converted by other microorganisms for complete mineralization.

5. Inorganic electron donor bioremediation: microbes use inorganic molecules such as ammonium ion, nitrite ion, hydrogen sulfide, reduced manganese, or reduced iron as electron donors, and obtain carbon from atmospheric CO_2.

   Principal end products: nitrate ion, sulfate ion, oxidized manganese, or oxidized iron.

6. Cometabolism: in some situations, the targeted contaminant does not provide sufficient energy to sustain the microbes. In these cases, a primary energy source is required to support the microbes, which will then produce enzymes that fortitously degrade the contaminant of interest.

   Principal end products: CO_2, H_2O, acids, and partially degraded intermediates.

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2 Classes and descriptions are adapted from Ref. 2.

7. Reductive dehalogenation: microbes catalyze a reaction that replaces a halogen atom with a hydrogen atom.

   Principal end products: dehalogenated hydrocarbons that may be further degraded by other mechanisms, and acids.

Methods of changing mobility:

1. Biosorption: microbial biomass transforms and/or sorbs hydrophobic organic molecules and inhibits contaminant movement. If the biomass is growth in the path of a migrating contaminant, it is sometimes referred to as a biocurtain.
2. Inorganic precipitation: microbes change the local environmental conditions so that insoluble reduced or oxidized metal species will precipitate.
3. Solubility enhancement: microorganisms alter the local environmental conditions and thereby keep contaminants in solution.

III. ADVANTAGES AND LIMITATIONS OF BIOREMEDIATION

The most important advantage that bioremediation offers over traditional clean-up methods is the potential to destroy contaminants. Whereas traditional methods transfer the contaminants to an accessible medium so they can be further treated, bioremediation chemically transforms the contaminants. Bioremediation holds great promise for treating a wide range of contaminants and reducing the cost of cleanup. *In situ* bioremediation in particular shares the advantages of other *in situ* techniques (physical or chemical) that reduce not only the cost of cleanup, but also the hazards and legal issues associated with the excavation and trucking necessary for *ex situ* and off-site techniques. In some instances, bioremediation allows continued use of the site during treatment. The advantages of bioremediation (particularly *in situ*) over conventional techniques have led to a rapid growth in the bioremediation field. In fact, "[b]ioremediation is one of the fastest-growing sectors of the U.S. hazardous waste market. It is expected to become a $500 million per year industry by the year 2000." (Ref. 2.)

It should be noted, however, that the advantages of bioremediation are not limited to those characteristic of *in situ* techniques. In some cases, the short- and long-term monitoring requirements and the inability to closely control the conditions in the subsurface may limit the cost-effectiveness of *in situ* techniques. In these cases, and in others where the state of the technology is less mature, *ex situ* techniques provide significant advantages over *in situ* techniques. Trade studies are necessary to evaluate the relative merits of either technique under site specific conditions.

Limitations of the technology:

Bioremediation is a scientifically intensive technology, requiring the collaboration of a large number of disciplines for a successful cleanup. Not only are the traditional disciplines such as engineering, chemistry, hydrology, and geology required, but also knowledge of the complex workings of microbes and microbial consortia. The interdisciplinary nature of bioremediation is in contrast to many physical or chemical remediation technologies and can impede its acceptance.

Technical limitations of the technology are summarized in Table 2.

Table 2. Technical Limitations of Bioremediation (adapted from Ref. 2)

- Transport problems: Unavailability of contaminants, nutrients, or electron acceptors necessary for function of the organisms.
- Toxicity: At high concentrations, contaminants may be toxic to the organisms.
- Selectivity: Non-target compounds may provide a better source of energy for the microbes than the target compound.
- Incomplete degradation: In some cases, the degradation pathway may not result in complete mineralization. The intermediate compounds may be toxic and/or refractory.
- Inability to meet regulatory objectives: Even if the degradation pathway can achieve complete mineralization of the target compound, concentrations that meet the regulatory limit may not be sufficient to maintain the microbial population. In this case, the bioremediation will not achieve acceptably low concentrations.
- Aquifer clogging: Accumulation of biomass or precipitation of inorganic oxides from the introduction of oxygen to the bioremediation system may significantly lower the hydraulic conductivity of the aquifer or clog well screens.
- Competition from indigenous microbes: For bioaugmentation, namely, the introduction of microbes to the subsurface, the inoculated organisms must compete with indigenous species. The survivability of inoculated microbes can be problematic.

IV. SERVICE-IDENTIFIED ENVIRONMENTAL REQUIREMENTS

Table 3 shows contaminants that are potentially amenable to bioremediation. Included in this list are only contaminants and matrices that the Services have identified for further environmental research and development. The numbers in the table correspond to the individual Service's priority for research and development. In other words, *chlorinated hydrocarbons in groundwater* is the Air Force's number one priority problem requiring environmental research and development. This table does not indicate the prevalence of a contaminant at DoD sites. Rather, it is indicative of each Services' understanding of the availability of effective and affordable treatment technologies. In Table 3, we also distinguish DoD-specific contamination from DoD-industry common contamination. A list of publically and privately funded demonstrations is documented in the EPA data base, *Bioremediation in the Field Search System*. In the Appendix, we summarize this data for the purpose of identifying areas where DoD technology demonstrations are likely to have a large impact on the development of biological techniques. Our recommendations reflect the relative levels of non-DoD investment in treatment strategies indicated in the appendix.

Table 3, while providing information regarding the types of contamination faced at DoD sites, does not quantify the prevalence of contaminants. Thus, in addition to the Services' indications of their environmental research and development requirements, Table 4 indicates the extent of various types of contamination at DoD sites.

We organize our discussion of bioremediation technologies based on the following categories of contaminants:

I. Organics

  A. Non-halogenated hydrocarbons
    1. General: Petroleum hydrocarbons, volatile and semi-volatile organics, and fuels
    2. Energetics
    3. Polycyclic aromatic hydrocarbons (PAHs)

  B. Halogenated hydrocarbons

II. Inorganics

Table 3. Environmental Contaminants Potentially Amenable to Bioremediation (adapted from Ref. 3.)

DoD-Industry Common	DoD-Unique	Contaminant	Medium*	Army Priority†	Air Force Priority†	Navy Priority†
X		**Organics:**	SO	12		
X			GW	8		
X		*Non-halogenated Hydrocarbons:*	SO			9
X			GW			6
	X	Energetics	SO	9		8
	X		SE	15		
	X		GW	4		
	X		W			4, 13
X		PAHs‡				
X		Pesticides, Herbicides	GW	8		
X			W			13
X			SO			14
X		Petroleum, Oil, Lubricants:				
X		Fuels				
X		Oil and Lubricants	W			13
X		*Halogenated Hydrocarbons:*	GW		1	7
X		CFCs (Chlorofluorocarbons)				
X		PCBs£	SO			14
X			W			13
X		PCPs, (Pentachlorophenol)				
X		Solvents (Halogenated)	SO			10
X			GW	5		
X		**Inorganics:**	SO	7		2
X			GW	21	3	
	X	Depleted Uranium	SO	19		
X		Hydrazine	SO, W		4	
	X	White Phosphorus	SE, SO	3		
X		**Mixtures:** Organics and Metals	SO	24		

* Key: SO = Soil; GW = Groundwater; SW = Surface Water; SE = Sediment; W = Water (not specified further).

† Priorities as defined in, "Environmental Technologies Requirements Strategy," Institute for Defense Analyses Document, Draft, 1994. Prepared for the Deputy Undersecretary for Defense, Environmental Security.

‡ Polycyclic aromatic hydrocarbons

£ Polychlorinated biphenyls

Table 4. Number of DoD Sites With Contaminants Above the Preliminary Remediation Goal Specified in DoD's Cleanup Program (Ref. 4)

	Soil	Groundwater	Surface Water	Sediment
Inorganics:				
Army	279	342	125	36
Navy	461	562	147	181
Air Force	562	735	250	
Total	*1302*	*1639*	*522*	*217*
Fuels:				
Army	29	109	7	9
Navy	209	270	12	88
Air Force	894	545	129	
Total	*1132*	*924*	*148*	*97*
Semi-Volatile Organic Compounds:				
Army	101	22	17	6
Navy	152	128	8	39
Air Force	246	246	42	
Total	*499*	*396*	*67*	*45*
Volatile Organic Compounds:				
Army	10	202	10	4
Navy	17	238	20	8
Air Force	52	430	49	
Total	*79*	*870*	*79*	*12*
Explosives:				
Army	54	46	43	3
Navy	29	33	2	4
Air Force	14	2	0	
Total	*97*	*81*	*45*	*7*

There are many possible taxonomies. However, we found this taxonomy to be particularly useful for discussing bioremediation technologies, as the utility of microbial and fungal systems depends on the chemical structure of the contaminant, not on its intended use.

Within each contaminant category the applicable technologies are divided by level of maturity into three categories: laboratory technologies, field-ready technologies, and commercially available technologies. Technologies that have been demonstrated at pilot scale straddle the first two categories. In general, we considered the presence of data from pilot scale experiments a necessary but not sufficient condition to consider a technology for field-level demonstrations.

V. ORGANICS

A. NON-HALOGENATED HYDROCARBONS

General: Petroleum Hydrocarbons, Non-Halogenated Volatile and Semi-Volatile Organic Compounds, and Fuels

Nature and extent of contamination

Non-halogenated organic compounds have been identified by the services as a high priority for research and development. The Navy is concerned about non-halogenated hydrocarbon contamination of soils, marine sediments, and groundwater; the Army, about contamination of soil and groundwater by organics. There is a great deal of overlap in the commonly used categories of petroleum hydrocarbons, non-halogenated volatile and semi-volatile organic compounds, and fuels. Because of this overlap and because of the similar treatment strategies for these compounds, they are discussed as a group, with issues of applicability of a technology to specific contaminants considered in each technology subsection.

Volatile and semi-volatile organic compounds (VOCs and SVOCs) are found in burn pits, chemical disposal areas, electroplating/metal finishing shops, firefighting training areas, hangars and other aircraft maintenance areas, landfills and burial pits, leaking storage tanks, oxidation ponds/lagoons, paint stripping and spray areas, pesticide/herbicide mixing areas, solvent degreasing areas, and vehicle maintenance areas. Most of these sites are caused by activities that are common to both DoD and the private sector. Examples of VOCs and SVOCs are shown in Table 5.

Fuel contamination can be found at many of the same sites where VOCs and SVOCs are found. Specific chemicals present in fuels include benzene, toluene, ethylbenzene and xylenes (BTEX), aliphatic hydrocarbons from propane to dodecane and higher with various substituents, and nitrogen-containing compounds such as pyridine.

Table 5. Examples of VOCs and SVOCs (Ref. 5)

VOCs	*SVOCs*
acetone	benzidine
acrolein	benzoic acid
acrylonitrile	benzyl alcohol
butyl alcohol	isophorone
methanol	nitroanaline
methyl ethyl ketone	butylbenzylphthalate
methyl isobutyl ketone	dibenzofuran
styrene	diethylphthalate
tetrahydrofuran	dimethylphthalate
vinyl acetate	nitromethylphenol
	pesticides/herbicides

Currently, soil vapor extraction, thermal desorption, and incineration are the EPA presumptive remedies[3] for soils contaminated with VOCs at Superfund sites. There is no presumptive remedy for water contamination, but air stripping, carbon adsorption, and UV oxidation are commonly used. There are no presumptive remedies for SVOCs or fuels in soil or water. Common treatments for these contaminants include biodegradation, incineration, low-temperature thermal desorption, and soil washing for soil contamination; air stripping and carbon adsorption are commonly used for water contamination. *In situ* bioremediation for water contamination is considered an innovative treatment since the control of the treatment process is difficult and poorly understood. Biological treatments for soils include both *in situ* techniques, such as bioventing and intrinsic bioremediation, and *ex situ* techniques, such as composting, bioreactors, landfarming, and slurry phase remediation. For treatment of light hydrocarbons, in particular, gasoline, jet fuel (JP-4), and some fuel oils, bioremediation is an established procedure.

Methods of biodegradation

Biodegradation of hydrocarbons can occur under either aerobic or anaerobic conditions. Because petroleum hydrocarbons are naturally occurring, microbes able to

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3 We refer to the EPA definition of presumptive remedies. The identification of presumptive remedies by the Superfund program is intended to shorten the time required to evaluate technologies and hence to more rapidly begin cleanup activities. As is the case with most remediation activities, however, the technical input of trained personnel is critical in the selection of the most appropriate site-specific remedy.

exploit these hydrocarbons as a food source have evolved in hydrocarbon-rich environments. These microbes are indigenous and ubiquitous. Using toluene as an example, aerobic degradation that results in the complete mineralization of the contaminant can be described by the reaction

$$C_7H_8 + 9O_2 \rightarrow 7CO_2 + 4H_2O$$

This reaction describes only the sum total starting and ending products. It does not attempt to address the mechanism of the transformation, nor does it delineate the multiple reaction steps that make up the degradation process, which are in many cases not well characterized. Complete mineralization may not always take place, and hydrocarbon intermediates may be left intact, or may be further degraded via other slower processes that do not use oxygen as the electron acceptor. Mineralization of hydrocarbons can also take place through biologically mediated reactions using alternate electron acceptors, such as nitrate or sulfate. Toluene under these nitrate- or sulfate-reducing conditions degrades via the reactions

$$5\ C_7H_8 + 36\ H^+ + 36\ NO_3^- \rightarrow 18\ N_2 + 38\ H_2O + 35\ CO_2$$

$$4\ C_7H_8 + 18\ SO_4^{2-} + 12\ H_2O \rightarrow 9\ HS^- + 9\ H_2S + 28HCO_3^- + H^+$$

But again, the mechanism for transformation is complex and not well understood, and the reaction may not proceed to complete mineralization, leaving residual hydrocarbon products.

Status of the technologies

Because contamination from VOCs, SVOCs, and fuels is prevalent across nearly all industrial activity, a great deal of effort has gone into developing bioremediation techniques to address removal of these contaminants. To decrease the cost and hazards associated with pump-and-treat and excavative methods, much of this effort has been directed toward developing *in situ* techniques. However, not all work has focused on *in situ* techniques. Landfarming and bioreactors are both on-site excavative methods of bioremediation. These techniques are discussed individually in more detail in the following sections.

One factor that limits biological treatment is the availability of an electron acceptor, in most cases oxygen, which is required by the microbes to metabolize hydrocarbons. Bioventing, air sparging, and hydrogen peroxide addition have addressed this limitation by increasing the supply of oxygen. The use of alternative electron acceptors, particularly nitrate, which is the most mature, is an attempt to utilize different microorganisms having

the ability to degrade the same or similar contaminants. The use of such microbes eliminates the need for oxygen entirely. Intrinsic bioremediation may be useful for sites where the natural supply of oxygen is sufficient.

Air Sparging. Air is injected under pressure below the water table to displace water in the saturated zone. This air flow both provides oxygen to assist in biodegradation of contaminants between the injection point and the surface and provides a physical means of removing contaminants through vapor phase extraction. Air sparging uses higher flow rates compared to bioventing (described below) to effect contaminant stripping from the groundwater. Heavier, low vapor pressure contaminants such as fuel oil and waste oil are removed primarily by biodegradation, while lighter, higher vapor pressure mixtures, such as gasoline, are removed to a significant extent by vaporization. Treatment of off-gases is necessary if contaminants are vaporized. Air sparging may spread the contamination plume underground if highly permeable layers are below denser, lower permeability layers, such as clay.

Currently, there is great debate over the effectiveness of air sparging. Originally, it was postulated that air injected into an aquifer would form many small bubbles that would travel vertically to the surface and present a large surface area for volatilization. However, more recently it has been suggested that the air injected into the aquifer travels primarily in the horizontal direction until it is intercepted by a monitoring well. This theory suggests that in the monitoring well substantial bubbling strips contaminant out, but elsewhere in the aquifer there is little or no stripping. It has also been postulated that the air injected during air sparging travels to the surface in a limited number of large channels. The amount of volatilization possible under such circumstances is substantially lower. It is certainly true that the injection of air into an aquifer creates a dynamic system that depends strongly on the heterogeneities at the site. (Ref. 6.)

The true effectiveness of air sparging systems is not now known, as the observed degradation at sites seems to be inconsistent with the simplest hypotheses. Thus, this technology is in need of field-level pilot tests that will resolve these questions. The tests cannot be conducted at the laboratory scale where it is impossible to reproduce the heterogeneities of the subsurface. (Ref. 6.)

Bioreactors. Excavated soils are mixed with amendments and placed in above-ground enclosures that include leachate collection systems and some form of aeration. The reactor is set up on an impermeable liner to prevent contaminant migration. Treatment takes place in either prepared treatment beds, biotreatments cells, or soil piles, where moisture,

heat, nutrients, oxygen, and pH are controlled. Either a vacuum or forced-air system is used for air distribution. This is an established technology that has been demonstrated at full scale. (Ref. 5.)

Bioventing. In bioventing operations, air is injected into (or drawn under vacuum through) the soil at low flow rates above the water table to stimulate the biodegradation of contaminants in the vadose zone.[4] Optimization of the airflow rate in a bioventing system is critical. The flow rate must be low enough to minimize volatilization and the formation of direct air channels to the surface, but must also be high enough to supply sufficient oxygen to the microbes. Even so, bioventing can result in vaporization of the contaminants, and the air stream can require air treatments as well. For example, in a bioventing treatment at a gasoline service station at Eglin AFB, Florida, it was estimated the biodegradation accounted for 65 percent of the removal of hydrocarbons from the site, while vaporization accounted for 35 percent. (*Downey* in Ref. 7.) In general, low vapor pressure substances (< 1 mm Hg) biodegrade with bioventing, high vapor pressure substances (> 760 mm Hg) volatilize, and substances with intermediate vapor pressures are removed through some combination of biotransformation and volatilization. Although bioventing is a mature technology that has been applied to more than 1,000 sites worldwide, controlled field demonstrations could provide information that may refine and improve current practices or expand its application to new classes of contaminants. (*Hinchee*, Ref. 8.)

Hydrogen peroxide addition. Water has only a moderate capacity for dissolving oxygen, so an alternative means of supplying oxygen to contaminated groundwaters by the addition of hydrogen peroxide solutions has been investigated. Hydrogen peroxide, which is infinitely soluble in water, decomposes via the reaction

$$2H_2O_2 \rightarrow 2H_2O + O_2$$

to produce molecular oxygen. A dilute solution of hydrogen peroxide, that is below the level of toxicity to microbes, can supply oxygen in quantities significantly greater than those available through injection of water saturated with oxygen. The toxicity level is highly dependent on the specific microorganisms involved, but hydrogen peroxide concentrations up to 1,000 ppm may be used to increase the oxygen concentration by up to 50 fold over that available by saturating water with air. (*Brown and Norris,* Ref. 7.) This

4 The *vadose zone* is the unsaturated region above the water table. It is also referred to as the *unsaturated zone*.

approach requires a circulation system to introduce the peroxide-containing water and to prevent contaminants from escaping the biotreatment zone. Like other *in situ* techniques, it involves maintaining nutrients, pH, and temperature at levels conducive to microbial growth. Hydrogen peroxide can be an expensive oxygen source. Furthermore, the injection of hydrogen peroxide may be limited by regulatory constraints.

There are a number of engineering challenges to applying hydrogen peroxide treatments in the field. It can be difficult to circulate the solution through different zones in a heterogeneous environment. Some geological strata, high iron content soils, or naturally occuring microbial enzymes can rapidly consume the hydrogen peroxide. Early *in situ* tests have illustrated some difficulties with hydrogen peroxide treatment: geochemical reactions around the injection point have resulted in clogging and poor oxygen transfer, often the hydrogen peroxide decomposes too quickly to remediate a wide area around the introduction point, and hydrogen peroxide treatment is also generally more expensive than air sparging or vapor extraction. (Ref. 5.) Nonetheless, hydrogen peroxide treatments have been successfully applied in the field. In a full scale operation at Great Slave Lake in Canada, groundwater and lake water contaminated with petroleum hydrocarbons, including benzene, toluene, ethylbenzene and xylenes (BTEX), were treated with hydrogen peroxide. The contaminated groundwater was pumped and enriched with nutrients and hydrogen peroxide, and then reinjected. From September 1990 to November 1992, the total petroleum hydrocarbons decreased by 75–80 percent. From the modest initial concentration of BTEX at the start of treatments, contamination decreased to below detectability limits. (*Carss, et al.*, Ref. 7.)

In situ bioremediation. In situ treatment is highly desirable as it does not require the excavation and transportation of contaminated media. Instead, the microbial species are stimulated with the addition of oxygen and/or nutrients. Generally, native species are capable of degrading the contaminants of interest, although indigenous populations may, in some cases, be augmented with non-native microbes. (The lack of success using non-native microbes, or bioaugmentation, is discussed in Section VII.) Because the contaminants are not removed for treatment, the dangers associated with the further migration of the contaminant plume and the creation of intermediates that may be more mobile, more toxic, and more refractory must be considered. *In situ* bioremediation has been successfully applied at field scale in the treatment of petroleum hydrocarbons, non-halogenated solvents, some pesticides, wood preservatives and other organic chemicals. Recent studies suggest that non-halogenated hydrocarbons can be remediated *in situ* using an aerobic/

anaerobic sequence. The Traverse City site in Michigan showed that once microbes are stimulated to degrade hydrocarbons aerobically, they will continue to degrade the hydrocarbons under anaerobic conditions. The degradation rate slows; however, the cost of remediation decreases substantially as the supply of oxygen is no longer required. This represents interesting possibilities for sites contaminated with both non-halogenated and halogenated hydrocarbons. (Ref. 6.) Several additional examples of specific *in situ* techniques are discussed separately in this report.

Intrinsic bioremediation. In intrinsic bioremediation, indigenous bacteria are allowed to biodegrade a contaminated zone without technological intervention. Generally, intrinsic attenuation is used to supplement other remediation techniques. Aerobic biotransformation can take place in the vadose zone and at the margins of plumes, where oxygen is not a limiting resource. In the core of the plume, anaerobic biodegradation reactions may occur. Intrinsic attenuation has been demonstrated at a number of petroleum hydrocarbon contaminated sites. Experiments have shown that BTEX compounds can degrade at rates of 0.5 to 1.5 percent per day. Although intrinsic bioremediation has no engineering requirements to benefit from a technology investment, there is great need for improved and more cost effective methods for demonstrating that contaminants are degraded and for identifying the degradation processes. Greater understanding of the underlying mechanisms involved is also needed, so that models can be developed to predict the level of intrinsic attenuation possible at contaminated sites. Intrinsic bioremediation is receiving more attention as an alternative to more costly site remediation techniques. (Ref. 9.)

Landfarming. Soils are excavated to treatment plots and periodically tilled to mix nutrients, moisture and bacteria. Operations must be conducted on impermeable liners to control leaching. Moisture, oxygen, nutrients, pH, and bulking materials must be maintained. Landfarming has been used extensively for petroleum hydrocarbons, particularly the heavier compounds including diesel fuels, fuel oils, JP-5 jet fuel, oily sludges and coke wastes, whereas bioventing is the preferred *in situ* technique for the treatment of the lighter hydrocarbons. Landfarming has also been demonstrated for PCPs and PAHs. Landfarming is a full-scale established bioremediation technology. (Ref. 5.)

Nitrate enhancement. The difficulty with providing oxygen has prompted investigation of alternative electron acceptors in biotreatment schemes. Of the various possibilities, nitrate has been the most thoroughly studied and has shown the potential for large scale *in situ* use. (*M. Reinhard*, Ref. 8.) Other electron acceptors, including sulfate

and carbon dioxide, have been documented in the laboratory, but are further from field ready. Nitrate is the most investigated alternative electron acceptor because it is inexpensive, water soluble, does not absorb onto soil matrices, does not decompose, and is second to oxygen in redox potential. However, the shift away from oxygen as a terminal electron acceptor decreases the rate of bioremediation. Nitrate enhancement is particularly promising for aromatic compounds, and success has been demonstrated with toluene, ethylbenzene, and xylenes, although not with benzene. Regulatory restrictions on the allowable concentration of nitrate in discharged waters limit the effectiveness of nitrate reduction for some classes of compounds. High molecular weight compounds are not readily degraded in nitrate systems, and aliphatic compounds are not amenable to nitrate dependent bioremediation. (*Reinhard,* Ref. 8.)

Nitrate dependent bioremediation of hydrocarbons has been demonstrated in the laboratory and evaluated at pilot scale. It has been used in a limited number of cases, but the technology is immature. Generally, the underlying science needs to be better understood, and there is a lack of successful completed and documented field demonstrations. More work is needed to characterize the end products of nitrate biotransformation. A nitrate enhancement pilot project is scheduled to begin in May 1995 at Eglin AFB. (Ref. 10.) Separately, a large scale demonstration is currently underway at a contaminated gasoline production site. (*Batterman, et al.*, Ref. 7.) It has been operating since 1991 with a removal rate of 1–15 grams of hydrocarbon per cubic yard per day. This removal rate is less than was observed in the pilot study. Complete removal of hydrocarbons is expected in about 5 years.

Requirements for full-scale operation

Table 6 summarizes the status of the bioremediation techniques applicable to the treatment of non-halogenated hydrocarbons, emphasizing the technical barriers to full-scale commercial application.

Energetics

Nature and extent of contamination

Wastes from organic energetic compounds contaminate water, soil, and sediments in environments where such chemicals are produced, processed and disposed. Specifically, wastes from the production and use of energetics and propellants are found in artillery/impact areas, contaminated marine sediments, disposal wells, leach fields,

Table 6. Status of Hydrocarbon Bioremediation Methods

Method	*Status and Requirements*
Air Sparging	Operated at full scale for the treatment of groundwater contaminated with volatile or semi-volatile organics despite questions about effectiveness.
Bioreactors	Full-scale demonstrations for the *ex situ* treatment of contaminated ground or surface water, sludges, or soils.
Bioventing	Full scale commercial technology for the treatment of soils contaminated with light hydrocarbons.
Hydrogen Peroxide Addition	Need to address the problems associated with flow of the solution through heterogeneous environments, oxygen transfer, aquifer clogging.
In situ Bioremediation	Has been used at full scale for the treatment of soils and groundwater.
Intrinsic Bioremediation	Has been used at full scale for the treatment of soils and groundwater. No engineering involved, but would benefit from research and development on evaluation and modeling techniques.
Landfarming	Full-scale commercial technology for the treatment of contaminated soils.
Nitrate Enhancement	Need better understanding of underlying science, characterization of end products. Scale up from pilot demonstrations has not been accomplished.

landfills, burial pits, and TNT washout lagoons. In addition to energetics and propellants, related nitoraromatic compounds are used in the synthesis of fungicides, insecticides, herbicides, pharmaceuticals, and dyes.

Over many decades, the Army has operated plants for manufacturing various explosives used in ordnance. The manufacturing process produced wastewater contaminated with energetics as well as other organic residues. "Red water" is a result of the manufacture of TNT and is of fairly well defined chemical composition, whereas "pink water" is any wash water associated with load, assemble, and pack operations or with demilitarization of munitions involving contact with finished TNT. As a result, the composition of pink water varies depending on the processes from which it is derived. Both red water and pink water are colorless as effluents and turn pink, red, or black when exposed to light. Traditionally, residual red and pink waters were placed in settling basins so solid particles could be removed. The remaining water was then transferred to unlined

lagoons or pits, resulting in the leaching of energetic residues into the soil and groundwater. The U.S. Army Cold Regions Research and Engineering Laboratory found that, in soil samples contaminated with explosives, TNT was the most common contaminant. Eighty percent of the samples contained TNT, 40–50 percent contained TNB (trinitrobenzene), and fewer than 40 percent contained DNB (dinitrobenzene) and DNT (dinitrotoluene). Even fewer samples were contaminated with RDX, HMX, nitrocellulose, nitroglycerin, or tetryl. (Ref. 5.) The Army stopped production of TNT in the mid-1980's, so it is no longer necessary to dispose of red water in the United States. However pink water is prevalent, mostly from demilitarization operations.

Currently, there are no presumptive remedies for treatment of soil, sediment or sludge contaminated with energetics at Superfund sites. The Department of Defense is developing five bioremediation treatments for energetics: aqueous phase bioreactor treatment, composting, land farming, white rot fungus, and *in situ* biological treatment. (Ref. 5.)

Methods of biodegradation

Over the last several years, pathways have been outlined demonstrating that the potential exists for biodegradation of energetic compounds. General pathways for degradation of energetics and propellants are given below, but in many cases these pathways represent only a first step in showing feasibility. Potential treatments based on some of these pathways are far from field ready.

(1) nitroaromatics, such as TNT, DNT

$-C-NO_2 \rightarrow -C-NO \rightarrow -C-NHOH \rightarrow -C-NH_2$

$-C-NO_2 \rightarrow -C-NH_2 \rightarrow -C=O \rightarrow$ ring cleavage $\rightarrow$ mineralization

(2) nitramines, such as nitroguanidine, RDX and HMX

$-N-NO_2 \rightarrow -N-NO \rightarrow -N-NHOH \rightarrow -N-NH_2 \rightarrow$ mineralization

(3) nitrate esters, such as nitrocellulose and nitroglycerin

$-C-O-NO_2 \rightarrow -C-OH \rightarrow$ mineralization

For nitroaromatics, reduction of the NO_2 groups is well documented, but only recently have ring cleavage and mineralization been demonstrated in experiments using radiolabeled TNT. Recent laboratory studies of fungal systems, particularly white rot fungus, show promise for ring cleavage. Nitroglycerin can be successively denitrated, and the resulting glycerol is biologically mineralized. Heavily substituted nitrocellulose is not, at present,

thought to be subject to biodegradation, but treatment with alkali produces a denitrated polymer that can be attacked by microorganisms. For RDX and HMX, aerobic conditions are not conducive to biotransformation, but mineralization has been observed in anaerobic cometabolic situations. Intermediates in the biodegradation of RDX and HMX include mono-, di- and trinitroso compounds. (Ref. 11.)

Status of the technologies

Bioreactors. Bioreactors can be of either the lagoon type, where the contaminants are left in a lagoon to which nutrients and water are added to enhance microbial activity, or the above-ground type, where groundwater or excavated soil mixed with water is enclosed in a surface construction. Treatments using lagoon-type bioreactors should be implemented cautiously until the degradation pathways are well understood and controls are well established. In either lagoons or above-ground reactors, the contaminated material is mixed with nutrients and oxygen and maintained as a suspension in the reactor. Bioreactors have been successfully applied to energetic sludges and groundwater, petroleum hydrocarbons, petrochemicals, solvents, pesticides, wood preservatives, and other organic chemicals. Bioreactors are preferred for treatment of heterogeneous soils and low permeability soils. Treatment times can be short, on the order of days, but material handling costs can be high. A demonstration of an anaerobic bioreactor for the treatment of TNT was recently conducted under the EPA SITE program. However, results are not yet available.

To date, demonstrations have been limited to laboratory and pilot scale, with problems still to be solved before transition to full scale. For example, in a biotreatability evaluation of sediment contaminated with the energetic pentaerythritol tetranitrate (PETN), laboratory and pilot scale studies were conducted. The first lab study was unsuccessful, but the second showed a decrease in PETN from 16,500 ppm to 356 ppm in 70 days. In the field study that followed, the concentration of PETN in a 1,000 m^3 test cell was decreased from 3,639 ppm to only 1,900 ppm after 2 months of treatment. (*Swindoll, et al.,* Ref. 12.)

Composting. Contaminated soils or sediments are excavated and mixed with bulking agents and organic amendments to encourage growth of indigenous bacteria and/or fungi. The mixture is maintained at elevated temperatures of 50–55 °C, achieved primarily from the heat generated by microbial activity. Moisture, pH, oxygen level, and the carbon-to-nitrogen ratio are maintained to optimize conditions for the microbes. If energetic contamination is above 10 percent by weight, the contaminated material is blended and

screened to dilute the energetic and produce a homogeneous mixture. Composting can provide both aerobic and anaerobic environments with the ability to treat both the nitro groups and the aromatic rings. The success of composting can be limited by the level of indigenous organisms, and there are long treatment times for some wastes. Decomposition of energetics can produce toxic byproducts, which must then be treated as hazardous wastes. Since 1982, various research groups have been working on composting treatments for soils contaminated with TNT, RDX, HMX, DNT, tetryl, and nitrocellulose. Laboratory and pilot studies have shown that composting can reduce the concentration of TNT, RDX, HMX to acceptable levels. In one field demonstration conducted by the USAEC at Umatilla Depot, TNT reductions up to 99.7 percent were observed in 40 days, with the majority of the TNT removed in the first 20 days. RDX and HMX were found to decay at up to 99.8 percent and 96.8 percent, respectively. (Ref. 5.) However, the end products of the process are unkown and may be toxic. Furthermore, composting significantly increases the volume of waste to be disposed.

In situ bioremediation. As discussed previously, bioremediation has been successfully applied in the treatment of petroleum hydrocarbons, solvents, some pesticides, wood preservatives and other organic chemicals. Pilot scale studies have indicated success with the treatment of nitrotoluenes. However, bioremediation of energetics typically requires cometabolism, which can be difficult to establish *in situ.*

Microbial Mats.[5] Microbial mats are complex consortia of aerobic and anaerobic bacteria that have shown the potential to treat a variety of contaminants. Since some intermediates of biological treatment of energetics are also toxic, mixed microbial systems, such as those in microbial mats, where a second type of bacteria will break down products of the first stage, are desirable. In one laboratory study, bacteria were taken from TNT-contaminated soil and exposed to increasing concentrations of TNT in acetone to build tolerance. Then microbial mats were constructed of the TNT tolerant bacteria. When these mats were used to treat an aqueous solution contaminated with 100 ppm TNT, the TNT concentration decreased by more than 99 percent in 6 days, although the end products were not documented. (*Mondecar, et al.*, Ref. 12.) Although laboratory studies of microbial mats have been promising, few rigorous evaluations using controlled systems have been conducted. Fundamental understanding of mass balance and ultimate end products is required before full scale demonstrations should be contemplated.

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5 Microbial mats are discussed more fully in Section VI, Inorganics.

Phytoremediation/constructed wetlands. Energetics-contaminated groundwater may be treated in a constructed wetland. The wetland construction contains both aerobic and anaerobic zones produced by a combination of microbes and higher plant species that provide advantages for treating explosives. Section VI on inorganics provides a more detailed description of constructed wetlands. A plant nitroreductase enzyme has been shown to degrade TNT, RDX, and HMX to environmentally acceptable products. Laboratory studies with radiolabeled TNT have demonstrated ring cleavage and incorporation of the products into the biomass; half-lives for degradation of TNT are on the order of minutes. Degradation of RDX, HMX, and other aminotoluenes associated with the explosive production process have also been observed. This has been demonstrated in scaled-up batch systems. Contaminated sediment and water were mixed with parrot feather grasses, and the residual concentrations of TNT and amino intermediates were observed to drop below 0.1 ppm. This technology has not yet been demonstrated at full scale. (Ref. 13.)

White Rot Fungus. Some bacteria are not able to degrade TNT, and nitroaromatics in general, to an acceptable byproduct, as the natural degradation process results in the reduction of the nitro groups but leaves toxic aromatic and amine residues. (However, recent experiments using radiolabeled TNT have demonstrated a significant degree of mineralization.) The ability of white rot fungus to treat some contaminants has been known for 10–15 years. White rot fungus has successfully degraded TNT in pure aqueous cultures in many laboratory and pilot scale tests. For example, a controlled laboratory study that used white rot fungus to treat a soil sample contaminated with TNT showed that TNT concentration was reduced by greater than 90 percent in 4 weeks. A pilot scale study of white rot fungus conducted under non-sterile conditions at a former ordnance open burn/open detonation site at Naval Submarine Base, Washington, showed a decrease in TNT concentration of 41 percent in 120 days, reducing the initial concentration of 1,844 ppm to 1,087 ppm in 120 days, but leaving contamination residuals well above the proposed cleanup level of 30 ppm. (Ref. 5.)

The results of these and other laboratory and pilot scale demonstrations show the potential for white rot fungal treatment of nitroaromatics, but there are a number of obstacles to be addressed in bringing the technology to commercial scale. These include competition from native bacteria, toxicity inhibition, chemical sorption, the inability to meet desired cleanup levels, and the engineering difficulties associated with the wood substrate required by the fungus. Many of the most promising studies to date have used sterile

conditions, where the fungus can grow free of competition. At field sites, there are native bacteria and fungi, and the introduced white rot fungus does not thrive in competition with indigenous species. Experiments imply that white rot fungus is viable under a narrow range of moisture, pH, oxygen, and nitrogen content conditions, and while duplicating these in the field may enhance its survivability, the cost and time associated with the transition to the field are as yet undetermined. The concentration of TNT typically found in field conditions inhibits fungal growth. More seriously, some reports of decreased TNT concentration can be attributed to adsorption of the TNT into the fungus and the accompanying soil amendments required to support the fungus, raising concerns about the level of biotransformation taking place. Finally, results such as those from the Naval Submarine Base demonstration raise some question about whether fungal treatment can be engineered to achieve acceptable cleanup levels. Little is known about the mechanisms of fungal transformation of TNT and, although some of the TNT can be mineralized, the other products from its biodegradation have not yet been identified. Thus, for all applications, questions remain about the ultimate fate of the contaminants and intermediates.

Laboratory and pilot scale demonstrations have shown that white rot fungus has the potential to degrade not only nitroaromatics (TNT) and nitramines (RDX and HMX), but also other difficult to degrade materials such as DDT, PAHs, PCBs and PCP. (Ref. 5.) However, in the many years of testing on white rot fungal systems, field-level experiments have failed to acheive the performance demonstrated in the laboratory. To the contrary, white rot fungus has performed poorly, as compared to laboratory results, in each field test conducted.

Requirements for full-scale operation

Table 7 summarizes the status of the bioremediation techniques applicable to the treatment of energetic compounds, emphasizing the technical barriers to full-scale commercial application. The end products and their potential hazards are a concern for all bioremediation of explosives. Bioremediation of energetics will probably be limited to low concentrations of explosives for the foreseeable future. Incineration or other conventional techniques are required to treat high contentration contaminants.

Table 7. Status of Bioremediation Methods for Energetic Compounds

Method	*Status and Requirements*
Bioreactors	Full scale commercial technology for treatment of hydrocarbons. Transition from pilot to full scale is needed for energetics. Technology used for aqueous and solid phases.
Composting	Field scale demonstrations for the treatment of energetics in soils have been conducted.
In Situ Bioremediation	Limited success at pilot scale for energetics treatment in soils.
Microbial Mats	Promising preliminary laboratory results for the treatment of contaminants in the aqueous phase. Need pilot and field demonstrations.
Phytoremediation/constructed wetlands	Some scaled-up batch systems. Predominantly laboratory or early pilot scale.
White Rot Fungus	Has been successfully demonstrated at the pilot level for the treatment of soils contaminated with energetics. For full scale applications, issues of competition with native species, toxicity of contaminants, sorption to the amendments, and attainable clean-up levels must be addressed.

Polycyclic Aromatic Hydrocarbons (PAHs)

Nature and extent of contamination

PAHs are common industrial pollutants that are produced during the refinement of crude oil and the manufacture of petroleum products such as plastics. PAHs are present in heavier petroleum hydrocarbon blends, particularly coal tars, wood treating chemicals, refinery waste sludges, and coking residues. Although PAH contamination is a serious problem for the petroleum industry, it is not a primary concern of the DoD.[6] We discuss methods of bioremediation for PAHs briefly, however, because substantial effort has been and continues to be directed in this area.

Method of biodegradation and status of technologies

PAHs are aerobically biodegradable under a narrow range of conditions, with the smaller two- or three-ring compounds more effectively treated than the larger compounds. Laboratory studies have shown that white rot fungus has the ability to degrade PAHs under highly controlled conditions. An EPA SITE demonstration of bioventing to degrade PAHs in soil is ongoing, and preliminary results are encouraging.

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6 PAHs in sediments are of concern to the Navy. Nevertheless, the Appendix shows that many demonstrations (using non-DoD resources) involving the biological degradation of PAHs are planned.

Success in treating PAHs with biological techniques has been limited in part because PAHs adsorb strongly onto subsurface solids. In laboratory studies, treatment with surfactants has shown promise for desorbing the PAHs to enhance biotreatability. Although they have been successful, these experiments have largely been limited to simple problems; for example, surfactants have been effective at removing hydrophobic organic compounds from gravel samples. In general, surfactants have posed problems in microbial systems. In some cases, the surfactant is toxic to the microbe of interest. In others, the surfactant serves as the preferred energy source, thus halting the degradation of the desired contaminant. Nevertheless, some hydrocarbon-degrading bacteria produce effective surfactants *in situ* that may not pose the problems of those artificially introduced, and may offer significant advantages even over commonly used industrial surfactants. Overall, the biotreatment of PAHs is emerging.

B. HALOGENATED HYDROCARBONS

Nature and extent of contamination

Halogenated hydrocarbons can in general be divided into two groups: halogenated aliphatics and halogenated aromatics. Halogenated aliphatics are straight-chain hydrocarbons with one or more of the hydrogen atoms replaced by halogen atoms; they are used primarily as solvents, in cleaning and degreasing activities, and as refrigerants. Chlorinated aliphatics are relatively soluble in water and do not sorb strongly to soils. For those that are regulated, the solubility of chlorinated aliphatics is generally orders of magnitude higher than the drinking water standard. Since they are also denser than water, these compounds penetrate aquifers and continue to be sources of groundwater contamination over extended periods of time. Halogenated aromatics have halogens substituted on one or more benzene rings. These substances are used as solvents and pesticides (e.g., chlorinated benzenes), fungicides and herbicides (e.g., pentachlorophenol), and have been used as heat transfer fluids in electrical transformers and capacitors (polychlorinated biphenyls). (Ref. 2.)

The use of chlorinated solvents in the United States began in the early 1900's when solvents, in particular chloroform, were imported from Germany. Significant production of carbon tetrachloride and chloroform began in the United States in the 1920's, and early production of perchloroethylene (PCE) and trichloroethylene (TCE) began in the 1930's. Large productions of PCE and TCE began in the 1950's. (Ref. 14.) As a result of their widespread use, chlorinated solvents and their natural transformation products represent the

most prevalent organic groundwater contaminants in the country. (Ref. 8.) Of the greater than 1200 current or future Superfund sites listed on the National Priority List (NPL), almost 40 percent have contamination by chlorinated hydrocarbons. Estimates of the cost of remediation of chlorinated hydrocarbons by EPA, DoD, and DoE total $500 billion in the next 50 years.

The problem of chlorinated solvent contamination is one that DoD shares with industry. Contamination from chlorinated hydrocarbons occurs in all media with the possible exception of surface water. Most chlorinated hydrocarbons have high vapor pressures and therefore are rapidly volatilized from surface water. A high vapor pressure places these substances in the category of VOCs; EPA presumptive remedies for VOCs in soil are soil vapor extraction (SVE), thermal desorption, and incineration. There are no presumptive remedies for VOCs in water or in air.

In DoD, the Navy is concerned with PCB contamination in soil, water, and sediments, as well as general chlorinated hydrocarbon contamination in all media. The Air Force's number one priority for environmental research and development is chlorinated organics in groundwater; this same problem is the Army's fifth priority. (Ref. 3.)

Methods of biodegradation

As recently as one decade ago, chlorinated solvents were not believed to be subject to bioremediation. However, transformation products were subsequently found in groundwater samples, thus leading to a search for the biological or chemical processes responsible for the degradation. (Ref. 8.)

There are two general methods for bioremediation of chlorinated hydrocarbons: anaerobic biodegradation followed by aerobic biodegradation of the intermediate products (anaerobic/aerobic cycling), or aerobic cometabolic biodegradation. For highly chlorinated compounds, a preliminary anaerobic process followed by an aerobic process is usually required. The anaerobic process is a cometabolic process that uses methanogens (a class of microbes that produce methane and for which oxygen is toxic) to catalyze dehalogenation reactions. There is limited evidence that, in some cases, anaerobes can completely dechlorinate tetrachloroethene to ethene, which is nontoxic and readily degraded by aerobes. (Ref. 2.) The aerobic biodegradation of less halogenated intermediates is accomplished cometabolically, using methanotrophs, for example. In cometabolic processes, microbes metabolize the primary food source and fortuitously produce enzymes that degrade the target contaminant. In the case of methanotrophs, methane is the primary

"food" source, and the degradation of the chlorinated hydrocarbon is incidental. Other microbes that can cometabolize chlorinated species rely on propane, toluene, phenol, and other organic compounds as their primary substrate. As the degree of chlorination diminishes, aerobic cometabolism can be used to treat the contaminants directly. Alternatively, some microbes have been engineered to metabolize the chlorinated substances without an additional energy source or inducer.

It should be noted, however, that ultimately the removal of chlorinated compounds from groundwater is limited by the presence of non-aqueous phase liquids.

Anaerobic followed by aerobic degradation. As mentioned above, the first step in the treatment of highly chlorinated compounds is an anaerobic cometabolic dehalogenation. The bioremediation of halogenated aromatics is limited by the dehalogenation process. As an example, for chlorinated aromatics, the benzene ring that is the "carbon backbone" of the compound is subject to aerobic or anaerobic bioremediation, the latter occurring more slowly than the former. However, highly substituted aromatics cannot be aerobically degraded. Therefore, one possible approach to the bioremediation of chlorinated aromatics in soils, sediments, or water is anaerobic dehalogenation followed by aerobic degradation of the residual compounds. (Ref. 2.)

Reductive dehalogenation occurs when microbes catalyze the replacement of a halogen atom with a hydrogen atom. Thus, a hydrogen source in sufficient quantities is necessary to successfully dehalogenate the contaminant. Several compounds may serve as hydrogen sources: hydrogen, methanol, ethanol, glucose, sucrose, formate, acetate, lactate, crotonate, toluene, benzoate, and butyrate are some examples. At some sites, one or more of these compounds may be present as the result of past activities, creating conditions that will induce anaerobic dehalogenation. In most cases, reductive dehalogenation produces no energy for the microbes, but rather detoxifies their environment. In this sense dehalogenation can be viewed as a defensive mechanism for the microbes. However, researchers are beginning to find evidence that, in some cases, energy may be derived from these reactions, and the anaerobes are thus able to completely dehalogenate and metabolize the contaminant to form innocuous chemicals. For example, recent research has shown that the dehalogenation process can transform vinyl chloride to ethylene, which is non-toxic. (Ref. 8.)

The reducing conditions required for reductive dehalogenation cannot be accomplished when oxygen is present. Since the reduction of oxygen releases more energy than is available from the reduction of the halogenated compound, the thermodynamics of the

system dictate that oxygen, if present, will be preferentially used as the electron acceptor. For this reason, in the subsequent degradation of the less halogenated compounds, the use of less energetically favorable electron acceptors such as nitrate, sulfate, or carbon dioxide can prevent "poisoning" any unfinished dehalogenation reactions and should be considered.

The subsequent aerobic degradation of the less chlorinated species is also a cometabolic process requiring the addition of a primary "food" substrate. This process is described in the following section. If the dehalogenation is complete, as in the transformation of PCE to ethene or ethane, then no additional food source is required. In this case, the establishment of aerobic conditions at the site is sufficient to complete the mineralization process.

Aerobic degradation by cometabolism. Aerobic degradation becomes more feasible for chlorinated aliphatics when the degree of substitution decreases. The less chlorinated ethenes can be degraded by cometabolism when methane, toluene, or phenol is supplied. (Ref. 2.) The transformation of the chlorinated compound produces little energy benefit for the cells and hence supports only minimal cell growth.

It has been known for some time that lightly chlorinated species can be aerobically oxidized, but it is only in the last decade that the potential for aerobic cometabolism of more halogenated species such as TCE has been documented. The cometabolic degradation of TCE using methane or toluene as the energy source for the microbes has been demonstrated in the laboratory (Ref. 15.) Further, chlorobenzenes, the less chlorinated PCBs, and the less chlorinated chloroaliphatic compounds, such as methylene chloride, readily serve as growth substrates for a variety of bacteria, and are good candidates for bioremediation. They are all rapidly mineralized under aerobic conditions.

The cometabolism of chlorinated hydrocarbons often produces unstable byproducts that can be further transformed by chemical or biological means, in many cases to mineralization. For example, the oxidation of methane produces methane monooxygenases, which can be exploited to convert TCE to a chlorinated epoxide. This epoxide is unstable and breaks down to form carbon monoxide, formic acid, glyoxylic acid and a range of chlorinated acids. These intermediates can be further transfromed to carbon dioxide, water, and chloride ion.

Status of the technologies

Complete mineralization of highly chlorinated compounds usually requires an anaerobic dehalogenation process followed by an aerobic process. Unless the initial anaerobic dehalogenation is complete, both of these processes are cometabolic. Although cometabolism is a natural process, it is substantially more complex than direct microbial metabolism of the target compound. The anaerobic/aerobic processes necessary to degrade highly chlorinated compounds require control of electron donors and acceptors as well as the addition of a primary "food" substrate for the microbes. As a result, most of this work has been accomplished in above ground bioreactors.

Much is already known about the cometabolic processes that govern the degradation of chlorinated hydrocarbons. However, there have been few full-scale field applications of this technology and there are "virtually no sufficiently well-document full-scale applications at present that can be used to guide design and application or that can be used to evaluate costs." (*McCarty,* in Ref. 8.) One possible exception is an experiment conducted in a test zone of a PCE-contaminated aquifer underlying a plant in Victoria, TX. During the course of the two-year experiment, initial concentrations of PCE, TCE, and DCE in the aquifer were reduced from approximated 1,700, 535, and 385 ppb, respectively, to below detectable levels. Notably, during the experiment, intermediates were also tracked. This monitoring provided indications of complete dehalogenation of PCE to ethene and ethane. The conditions necessary for degradation were acheived by pumping benzoate or sulfate solution into the groundwater to achieve sulfate-reducing conditions. Mass balances using bromide tracers showed mass conservation to within 74 percent, and estimates of the mass of PCE and the intermediate products indicated conservation to within 64 percent. A control site was also established and no degradation of PCE was observed in the absence of biostimulation. (*Beeman, et al.,* in Ref. 16.) However, additional experiments at other sites are required, since the applicability of sulfate-reducing anaerobic conditions is not fully understood. There is some evidence that nitrate-reducing conditions can significantly inhibit dehalogenation. The effectiveness of various reducers may depend heavily on site specific conditions, the redox potential of the chlorinated solvent, and the microbial species present at the site. Not enough information is available to formulate general conclusions. (Ref. 6.)

Requirements for full-scale operation

The advancement of this technology requires full-scale experiments. The initial experiments are likely to be fraught with surprises and will fail to achieve cleanup goals.

Nevertheless, the level of understanding of this technology has progressed sufficiently that full-scale experiments are desirable. (Ref. 8.) The complexity of cometabolic processes requires that routine procedures for implementing anaerobic/aerobic sequencing be established before the technology can be applied at commercial scales to bioremediate sites contaminated with chlorinated aliphatics. (Ref. 2.)

A significant problem with the use of anaerobic biological dehalogenation followed by aerobic degradation of intermediates is that, in some cases, the intermediate compounds are more toxic and more refractory than the original contaminant. For example, one of the intermediate byproducts of TCE dehalogenation is vinyl chloride (VC), which is a known carcinogen. The presence of this intermediate is unavoidable in anaerobic/aerobic systems. VC has been shown to be degraded in aerobic systems, but it can be refractory if the system remains anaerobic, i.e., if methods to provide the system with oxygen fail. The presence of VC is a measure of whether the reductive dehalogenation is proceeding and is necessary before the aerobic phase of the remediation can begin. Nevertheless, it may be unacceptable from a regulatory point of view to enhance the production of VC for *in situ* applications.[7] If any natural dehalogenation is occurring, there will likely be VC present at the site and, in such cases, it may be possible to gain regulatory acceptance for enhancing the anaerobic dehalogenation process. For *ex situ* applications, this is not an issue.

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7 The regulatory position on the generation of vinyl chloride depends on the half-life of the compound at the site of interest.

VI. INORGANICS

Nature and extent of contamination

Contamination from inorganics is the result of mining and industrial activities, including electroplating, metal finishing and vehicle maintenance. In addition, common industrial activities result in battery disposal areas, burn pits, chemical disposal areas, disposal wells, and leach fields, all of which may be contaminated with inorganics, predominately heavy metals. Military testing and training activities also create unique inorganic contamination problems such as those at artillery and small arms impact areas. (Ref. 1.) In the category of inorganics, the Services have identified the following contaminants as problematic: heavy metals, depleted uranium, hydrazine, and white phosphorus. We discuss only methods for treating heavy metal contamination.

Heavy metals commonly found as contaminants at industrial facilities include chromium, copper, nickel, lead, mercury, cadmium, and zinc. Table 3 shows that inorganics in soil were identified as high priorities for the Navy and the Army. Inorganics (usually this refers to heavy metals) in groundwater and white phosphorus in sediments and soil are also identified as problem areas. Because of the prevalence of inorganic contamination caused by mining activities, the U.S. Bureau of Mines and the Colorado School of Mines have been actively involved in this area of research.

Methods of bioremediation

Metals are commonly regarded as inhibitors of microbial processes aimed at remediating organic compounds. In fact, metals and salts can limit biological activity, and high concentrations of metals are often toxic to microorganisms. At the same time, some metals such as cobalt, copper, or iron are necessary in small quantities as nutrients. To protect themselves from certain toxic metals, some microorganisms (and some plants) have developed processes to transform or isolate metals. These processes can be manipulated into a remediation strategy for metals contamination.

Microorganisms cannot degrade metals, but they can affect the mobility, toxicity, or reactivity of some metals. Microbes may decrease metal solubility through complexation reactions, pH manipulation, adsorption, or uptake. In mining operations, microbes have

been used to enhance the recovery of metals from low-grade ores. This process, called bioleaching, uses acids produced by the microbes. Metals can also be immobilized by microbes through incorporation into the biomass, or through valence state changes that cause the metals to precipitate. In biosorption processes, the volume of contamination is reduced by sorption of the contaminant into a more chemically stable matrix, namely the biomass. Alternatively, microbes can lower the redox potential, which may in turn (1) lower the toxicity of the metal or (2) lower the aqueous phase solubility of the metal thereby precipitating the inorganic material. In the case of chromium, biological processes have been shown to transform chromium (VI) to chromium (III), which has significantly lower solubility and toxicity. To date, the demonstrated biological processes do not employ microorganisms that act directly on the chromium, but rather microorganisms that alter the environment *in situ* to reduce the metal to a less hazardous state.

In each of the above described methods, microbes either actively or passively change the bioavailability of the toxic metal. Biological remediation of metals is simply an alternative for common chemical techniques. In many cases, the overall reactions are the same. There are two general disadvantages associated with using biological systems for the remediation of metals. First, biological processes are usually slower than chemical processes, and second, biological processes rely on living cells that are often not capable of tolerating high metal concentrations. Changes in the subsurface environment may also return immobilized metals to more mobile states. Nevertheless, biological systems have some distinct advantages for certain applications. For example, biosorbents have a high loading capacity at low metal-contaminant levels. In other words, they are able to treat low concentration influents and reach low effluent concentrations. Biosorbents are also more selective for transition and heavy metals, and thus are more effective for waters with high sodium or magnesium concentrations. (Ref. 17.) Finally, biosorbents have the advantage of not requiring chemical additions to the environment, which in some situations has distinct regulatory or public relations advantages.

The bioremediation of inorganics may take several forms. Some of these processes are discussed below. Most of them are in their infancy, some have been demonstrated at the bench scale, and fewer still have been demonstrated at the pilot scale.

Bioaccumulation/Biosorption. Bioaccumulation or biosorption works by transferring the metal from the contaminated matrix to the biomass, exploiting the ability of certain plants and microbes to absorb and accumulate metals in their cells. Predominantly, this transfer occurs from the aqueous phase, and it can be accomplished using either living

or dead cells. In living cells, heavy metals are not essential for metabolic activity. Thus, they are either taken up incidentally, when the plant or cell conducts other normal functions, or they are taken up to protect the organism from the toxic effects of the metal in its environment. In dead cells, sequestering occurs mostly by absorption to the cell surface. This process usually results in a more stable chemical complex for the metal.

Biobeneficiation. In biobeneficiation, microbes are used to improve the physical separation of a contaminated solid matrix into contaminant-rich and contaminant-poor streams. Loosely, biobeneficiation can be thought of as a microbially mediated distillation process. This method of bioremediation is typically applied in froth flotation systems, where particles with a hydrophobic surface are attracted to air bubbles formed by introducing air through crushed rock. Hydrophilic particles settle to the bottom. This process separates hydrophilic mineral concentrates from hydrophobic tailings. Froth flotation usually requires chemical treatment to maximize separation. However, biological action could replace chemical action in conventional flotation processes. For example, it is standard practice to add cyanide ions to ore pulp containing iron sulfide (pyrite). The cyanide ions form an iron-cyanide complex on the surface of the froth flotation system. The presence of this complex prevents pyrite particles from attaching to bubbles, which helps to selectively separate the desired metals. Some microbes have also been studied for the purpose of modifying ore surfaces to improve flotation processes or to improve settling or filtration by controlling agglomeration. Some microbes serve as flocculating agents and still others have been tested for recovery of kerogen (asphalt-like material) from oil shale.

Most biobeneficiation techniques are used specifically for improving the performance of physical separation in flotation and settling processes containing sulfide ores. (*Smith, et al.*, Ref. 18.) Biobeneficiation will likely be of limited use outside of the mining industry, although it might be useful in the treatment of marine sediments that have been contaminated with metals as the result of ship maintenance activities.

Bioleaching. Bioleaching refers to the microbial solubilization of metals to remove them from either a solid or a semi-solid matrix. Microbial solubilization can be achieved either by indirect methods (i.e., as a result of metabolic products), or by direct methods (i.e., cell metabolism), or by both. This process may be used either *in situ* or *ex situ*.

Currently, bioleaching is used in the mining industry on a industrial scale for improving yields of valuable metals. *In situ* biologically-enhanced extraction of copper or uranium from low concentration raw ore is a common practice. *Ex situ* bioreactors are required for higher concentration ores. These new bioreactors are now being developed to

compete with chemical reactors. Some hypotheses exist regarding the specific organisms and pathways responsible for bioleaching. However, the exact systems of microorganisms and mechanisms are not yet fully developed, as is the case with many microbially mediated reactions.

Bioleaching is under development at the bench or pilot scale for a wide range of metals. The process is most advanced for the leaching of gold and silver pyrites or arsenopyrite ores. However, other metals are also under study, such as aluminum, cadmium, chromium, iron, lead, magnesium, mercury, molybdenum, nickel, selenium, and tin.

Constructed wetlands. The passive bioremediation of metals in wetlands is a concept borrowed from geomicrobiology. The goal in wetland remediation is to return metals to their natural mineral form. Typically, minerals are formed over geologic time scales; thus, the naturally occurring mineral form of a metal is also generally its most stable chemical form. Many minerals are formed in the presence of water via reactions that are catalyzed by microbes in processes that are part of the natural global cycling of metals. Bioremediation using constructed wetlands involves harnessing and optimizing this process. (*Wildeman, T.R., et al.*, Ref. 18.)

A wetland system typically has an aerobic region at the surface and an anaerobic region below. Biologically catalyzed redox reactions play a major role in the removal of metals from both regions. Under aerobic conditions, metals with insoluble oxides such as Fe(III) and Mn(IV) are removed. Anaerobic processes, such as sulfate reduction, remove metals that form insoluble sulfides such as Cu, Zn, Cd, Pb, Ag, and Fe. Both aerobic and anaerobic processes can neutralize acids. This means that metals such as Zn and Cu can be removed as carbonates in either environment. (*Wildeman, T.R., et al.*, Ref. 18.)

The aerobic microbial processes of importance in wetlands include iron oxidation and photosynthesis. Both use CO_2 as the source of carbon for the organisms, and the pathways have been identified by Wildeman, *et al.* The anaerobic microbial processes of importance in wetlands include hydrolysis of biopolymers by extracellular bacterial enzymes, fermentation, methanogenesis, sulfate reduction, and iron reduction. To allow the other processes to be carried out, sulfate reduction and fermentation must be carefully balanced in a constructed wetland to maintain the pH within appropriate levels. (*Wildeman, T.R., et al.*, Ref. 18.)

Wetlands consist of complex microbial consortia. Most of the microbes in constructed wetlands are indigenous species. Organic soils, microbial fauna, algae, and vascular plants all contribute to the reduction of metals in the aqueous solution. Precisely because the system is complex, the pathways are not completely understood, nor are the interrelationship and balance between the aerobic and anaerobic processes. Nevertheless, it appears that balancing the aerobic and anaerobic zones is part of the effectiveness of the wetland system. Thus, the aerobic and anaerobic zones are linked, in that the aerobic zone, which contains blue-green algae and plants on the surface of the system, increases the pH and produces organic material important for survival of the sulfate-reducing bacteria.

Some metals remediation can occur in anaerobic systems alone. These pathways are less complex because they do not require plants, and microbial processes dominate the remediation. For example, some methods have been developed for increasing the pH of acid mine drainage and for metals removal through anaerobic wetland processes. The predominant mechanism for pH change is the reaction of acid with sulfide generated from sulfate-reducing bacteria. Some methods have been shown to increase the pH from 3 to 6 and to reduce metal concentrations (see Table 8).

Table 8. Selected Results of Wetland Bioremediation of Metals

Metal	*Initial concentration (ppm)*	*Final concentration (ppm)*
Iron	30	< 1
Copper	1	< 0.03
Zinc	9	< 0.03

(Adapted from *Wildeman, et al.*, Ref. 18.)

Methylation. Methylation refers to the ability of some microorganisms to attach a methyl group ($-CH_3$) to the inorganic form of metal. This process results in the formation of organometallic compounds with higher volatility than the elemental form of the metal. These organometallic compounds may subsequently be removed by volatilization and collected from a gas stream. Metals subject to methylation (or demethylation) include mercury, arsenic, cadmium, and lead.

Methylation has been demonstrated at the bench scale to remove arsenic from soil and sediment; however, it is unlikely to be used at contaminated sites in the near future. Although the methylation process makes the inorganic more available for treatment, it also makes the contamination more difficult to control. The organometallic compounds may

leach or pose air emission problems. Further, the toxicity and availability of the metal to humans is also typically increased, as is the case for mercury methylation.

Microbial mats. Microbial mats are like constructed wetlands in complexity and function; however, they do not include higher forms of life such as plants. Microbial mats are composed of complex consortia of microbes attached to a supporting matrix in an aqueous environment in which several coherent layers are formed. Photosynthetic cyanobacteria form the largest segment (or layer) of the microbial population and are responsible for providing nutrients to the mat community. These bacteria also contribute to the ability of the mat to sequester metals.

Laboratory column experiments have demonstrated the removal of metals, and controls indicate that sorption to the mat matrix provides only limited metal removal. In addition, x-ray microanalysis of the microbe cells indicates that the metals are deposited along the surface of the mat rather than within the cell structure. This suggests that cell sorption is not the mechanism of removal by the mat microbes. In still other laboratory column experiments, microbial mats have been shown to be "durable, resilient, and tolerant of wide environmental fluctuations." (*Rodriguez-Eaton, et al.*, Ref 18.) These mats have been shown to release metal-binding flocculants as well as to simultaneously degrade chlordane, TNT, and petroleum distillates. There appears to be a strong correlation between protein flocculants produced by microbial mats and the precipitation of some metals, in particular iron, manganese, and zinc. Removal rates were on the time scale of days, and the removal efficiencies were between 80 and 90 percent. (The removal of manganese is thought to be due in part to coprecipitation with iron.)

It should be noted that in most laboratory experiments using microbial mats, the chosen substrate is inoculated with microbes that have been "conditioned" and are thus resistant to the high concentrations of imposed contaminants. Nevertheless, many of these laboratory experiments have been conducted using actual waste streams, such as acid coal mine drainage, rather than sterile simulants.

Furthermore, it is not likely, given the complexity of a microbial mat system, that the pathways for contaminant destruction or isolation will be understood in the near future. Nevertheless, before microbial mats can be further advanced as a remediation technology, a better understanding of the mass balance of the system, the potential formation of intermediates, and the ultimate fate of inorganics upon death of the microbial system is required. These issues need investigation, especially at scales larger than laboratory columns. At laboratory scales, controls indicate that some "apparent" degradation or

sequestration is due to adsorption, but the complexity of the system often provides microbes that will degrade intermediates as well as the parent contaminant, and metals are typically precipitated or deposited at the mat surface rather than within the cell mass. Whether the mat is sequestering or adsorbing the inorganic material is important in determining the long term fate of the inorganics. Thus, while microbial mats are especially promising for the remediation of mixed aqueous contaminant streams, additional tests at larger scales are required before a field-level demonstration is likely to be useful.

Redox reactions. Some microbes oxidize or reduce metals, i.e., they perform reactions that result in the exchange of electrons, which changes the valence state of the metal. In this process, the microbe either actively performs the reaction at some energy cost to the cell, or it secretes a reducing agent. The redox reactions can change the mobility of the metal either by increasing its solubility in the matrix to make it available for treatment or by decreasing its solubility to precipitate the metal. Microbially mediated increases in the solubility are not unlike other chemical or physical treatment processes such as soil washing or chemical leaching.

Redox reactions may happen indirectly as a result of other microbial activites, as in the case of sulfate reduction. Sulfate reduction is an anaerobic process in which bacteria oxidize simple carbon substrates using sulfate as the electron acceptor. This redox reaction produces hydrogen sulfide (H_2S) and bicarbonate (HCO_3^-). The H_2S will react with contaminant metals to precipitate them as insoluble metal sulfides. For example:

$$H_2S + M^{2+} \rightarrow MS(s) + 2H^+$$

The production of alkaline bicarbonate increases pH and may result in metal removal through formation of insoluble metal hydroxides or oxides. The process follows the reaction:

$$M^{3+} + 3OH^- \rightarrow M(OH)_3(s)$$

The stimulation of sulfate reduction and the resulting precipitation of metal oxides can be an inadvertent problem in some bioremediation projects aimed at organic compounds. In such cases, the formation of metal precipitates may clog the aquifer.

As an example of a biologically mediated redox reaction, consider the reduction of Cr(VI) to Cr(III). Cr(VI) is extremely toxic to most microbial systems. However, some tolerant strains are known to exist. These strains exist in part because the extreme toxicity of Cr(VI) "motivates" them to undertake a reduction reaction that transforms the Cr(VI) to

Cr(III), which is considerably less toxic. Several aerobic and anaerobic microbes that reduce Cr(VI) are known. *Bacillus subtilis* is one such microbe; it is common in soils and is not a pathogen.

Microbes can reduce chromium either by direct microbial action or by the production of hydrogen sulfide. Some processes have been developed by which Cr(VI) is reduced by the production of H_2S as described above. There are several organizations studying the reduction of Cr(VI) by direct microbial metabolism. In direct microbial metabolism, Cr(VI) diffuses through the cell wall, binds with an enzyme, and is reduced. Currently, reduction by sulfide production, which is an indirect process, is faster than direct processes. Some work has also been performed on a dialysis culture system that employs an anion-selective membrane to protect the bacteria from the toxic effects of chromium. The bioreactor is anaerobic; chromate diffuses through the membrane and is reduced to Cr(III), which exists in solution as a cation that cannot diffuse back through the membrane.

Vegetative uptake. Exploiting the ability of plants to concentrate metals in biological matrices is a relatively new field. Higher plant species require highly developed defense mechanisms that can be harnessed for bioremediation. In addition, some plants are capable of synthesizing complex organic molecules (i.e., rubber, turpentine, and medicines atropine and quinine). (Ref. 19.) Because plants are able to mediate complex chemical reactions, it is reasonable to expect that they might be able to degrade toxic chemicals in order to survive.

Higher plants can remediate contaminants in two ways. The plants either convert the contaminant into other species that are less toxic, as is the case with TNT or PCB, or they sequester the contaminant to remove it from the plant's metabolic activities, as is the case with most metals. To accomplish either, the plant must first convert the contaminant to a polar substance to improve its solubility in water, and thus enhance its mobility within the plant matrix. The plant then metabolizes the contaminant to decrease toxicity or sequesters the contaminant by linking it to other molecules to form a larger, more complex molecule of reduced solubility that is incorporated into the plant structure.

Certain plant species concentrate metals by uptake in the roots and deposition in the leaves. To grow, some plants require specific minerals that are considered undesirable contaminants, and these plants thrive only in environments that include these minerals. This is the case for several varieties of the *Leguminosae* family and locoweeds, which will often grow only on shale soils containing selenium and barium.

Vegetative uptake as a remediation procedure is in the preliminary stages of development. Most of the work to date has been performed in sterile suspended cell cultures with strict control on the environmental factors such as temperature and "food" source. Limited work with full plants has been performed. Some pathways have been mapped out, but most of the conversion processes are not understood. One significant advantage of vegetative uptake is that, in general, plants are able to withstand higher concentrations of contaminants than are microbes. However, the danger associated with contaminants moving up the food web must also be considered.

Status of the technologies

The biotreatment of metals is widely considered an emerging field; most technologies are in their infancy. The exception is biosorbents, which have been shown to remediate metal ions and are available commercially. In many cases, bioaccumulation has been shown to be as effective as ion exchange resins for the removal of metals from aqueous solutions. Bioleaching and biobeneficiation have also been used commercially in mining operations, but are unlikely to have widespread use in remediation applications.

Currently, most techniques for the bioremediation of inorganics are at bench scale. Nevertheless, there is considerable ongoing work on constructed wetlands and microbial mats. A constructed wetland was studied under the EPA SITE emerging technology program, and a full-scale wetlands project is planned under the EPA SITE demonstration program. To date, most of the work on wetland systems has been accomplished in smaller scale reactors. A pilot-scale system at the Big Five Tunnel in Idaho Springs, CO, has been in operation for 2 years. The pilot system is an anaerobic constructed wetland used to treat acid mine drainage. (*Wildeman, T.R., et al.,* Ref. 1.)

The ultimate utility of biological processes for the remediation of metals is difficult to predict. A comprehensive treatise is probably not possible for 5 to 10 years. (*Smith, et al.*, Ref. 18.)

Requirements for full-scale operation

Questions persist regarding the ultimate fate of inorganics incorporated into the biomass for *in situ* processes. Recent studies have indicated that, in the case of active microbial uptake of metals, death of the microbes can result in rerelease of the contaminants. Since nearly all biological techniques for the remediation of metals have shown some sorption of the contaminant in the biomass, *ex situ* bioreactors are preferred. Until constructed wetlands can be shown definitively and permanently to immobilize

metals, they will likely have to be closely monitored systems that more resemble bioreactors. Nevertheless, the robustness of wetlands and microbial mats to mixtures of contaminants makes these systems promising for the treatment of complex wastes. With few exceptions, most biological techniques for the treatment of metals still require scale up and demonstration outside of sterile laboratory conditions.

Table 9 summarizes the status of the bioremediation techniques applicable to the treatment of inorganic compounds.

Table 9. Status of Bioremediation Methods for Inorganic Compounds

Method	*Status and Requirements*
Bioaccumulation/ Biosorption	Commercially available for certain metals using dead cells or processed biomass. Living systems have been tested, but are not at commercial stage.
Biobeneficiation	Used commercially in some mining operations.
Bioleaching	Used commercially in some mining operations.
Constucted Wet Lands	Demonstrated at pilot level under EPA SITE emerging technology program. Planned demonstration at full-scale.
Redox Reactions	Demonstrated at the bench scale, but has not yet been demonstrated at the pilot scale.
Methylation	Laboratory scale demonstrations.
Microbial Mats	Laboratory and bench scale demonstrations.
Vegetative Uptake	Bench scale demonstrations.

VII. A FEW WORDS ABOUT GENETICALLY ENGINEERED MICROBES FOR REMEDIATION

New capabilities in genetic engineering suggest the possibility of creating microorganisms that are tailor made for the bioremediation of particular pollutants. However, as the purpose of this study is to evaluate field-ready technologies, we comment only briefly on work in the area of genetically engineered microbes (GEMs), which are years, if not decades, from field application. There are two types of hurdles that GEMs must overcome before commercial applications can be seriously considered: technical problems associated with competition and survival, and acceptance problems of both regulators and the public.

Technical issues. If GEMs are to be an effective addition to currently available bioremediation technologies, they must be able to thrive in an environment of competition from indigenous microbes. There have to date been no attempts to release GEMs for bioremediation into a natural environment, but studies of bioaugmentation (introducing naturally occurring but not indigenous bacteria to a site) may provide some insight into the survivability problem. There have been few direct comparisons between biostimulation and bioaugmentation, making it difficult to determine whether reductions in contaminants attributed to introduced organisms were in fact due to those organisms or were, rather, due to beneficial effects of the accompanying soil amendments on indigenous populations. Generally, the results of introduced microorganisms have been inconclusive. In the case of petroleum hydrocarbons, the effect of inoculation is generally negligible, presumably because petroleum degrading bacteria are ubiquitous. For PAHs and chlorinated species, particularly in areas of high concentration, a beneficial effect of inoculates is seen in some instances. (*Thomas and Ward*, Ref. 8.)

There has been some progress in the attempt to encourage introduced bacteria to survive in non-sterile environments. Laboratory experiments have shown that introduced organisms generally do better when combined with some type of carrier material such as agar, peat, alginate, or a fluid gel. This procedure allows high concentrations of an organism to be introduced, provides nutrients and a moisture reserve, and isolates the new organisms from predators. Lab evidence indicates that this procedure of sending a "lunch box" with the microbes enhances survivability. Nevertheless, this approach will be

difficult to engineer at large scales. In addition, this approach does not address all of the survivability problems unique to genetically altered organisms. For example, these organisms may, in the process of genetic manipulation, lose traits that allow them to survive in the environment. On the other hand, post-release genetic mutations may cause genetically altered organisms to lose the traits that allow them to degrade contaminants. (*Thomas and Ward*, Ref. 8.)

Acceptance. There are three interrelated issues to be considered in the area of acceptance: the debate about the scientific and ethical considerations of releasing genetically engineered organisms into the environment, the public perception of that debate, and the regulatory constraints imposed. There have been in excess of 100 tests of genetically modified microorganisms, most of which are to be used as pesticides. The first of these tests was highly controversial, but this and later tests have all been conducted safely with no incidents, so the regulatory atmosphere has relaxed to some extent. Currently, the EPA requires a premanufacture notice for use of GEMs, and permission for use in a contained bioreactor is readily available. There is currently a proposal for a contained bioreactor to degrade TCE vapor in air stripped from contaminated groundwater. Initial field trials show an average 90 percent degradation. However, as an indication of the state of GEM technology for use outside of contained reactors, consider that as of March of 1993, no applications had yet been filed for this purpose.

VIII. RECOMMENDATIONS

The goal of this study was to identify field-ready bioremediation techniques that could benefit from additional demonstrations to gain information at the field level and hence to prove or disprove the technology for widespread use. Table 10 shows our understanding of the current state of the technology for various biological techniques. In addition, Table 10 includes pertinent information for selecting technologies that might benefit from additional demonstrations and ultimately extend the use of bioremediation by DoD. There are a number of technologies already applicable at commercial scale as well as a number of technologies that are too immature to benefit from field-level demonstrations.[8] The former include bioventing, landfarming, composting, and metals treatments used by the mining industry, while the latter include genetically engineered microorganisms and non-mining treatments for heavy metal contamination. Only a few technologies are at a stage to merit further consideration. They are bioreactors for treatment of energetics, *in situ* anaerobic/ aerobic sequential treatment of chlorinated hydrocarbons, constructed wetlands, and white rot fungus. We strongly recommend the first three technologies as candidates for field-level demonstrations; the fourth we recommend less enthusiastically.

Bioreactors for treatment of energetics. Bioreactors can be of either the lagoon type or the above ground type. Treatments using lagoon-type bioreactors should be viewed with caution until the mechanisms of degradation are well understood and controls are well established. Bioreactors have been applied to sludges and groundwater contaminated with energetics, petroleum hydrocarbons, petrochemicals, solvents, some pesticides, wood preservatives, and other organic chemicals with varying degrees of success. Treatment times can be very short, on the order of days. Demonstrations have been limited to laboratory and pilot scale, with problems still to be solved before the technology can be brought to full scale.

In situ anaerobic/aerobic sequential treatment of chlorinated hydrocarbons. For highly chlorinated organic contaminants, anaerobic reductive dehalogenation followed by

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8 Appendix B is a list of the technologies considered in this study.

Table 10. State of Bioremediation Technologies and Other Relevant Factors

Contaminant	*DoD Priority*	*Biotreatment*	*State of Technology and Needs for Full Scale Use*
Non-halogenated Hydrocarbons	Medium	Air Sparging	Full scale, actual effectiveness questionable
(POLs, VOCs,		Bioreactors	Full scale
and SVOCs)		Bioventing	Full scale commercial treatment
		Hydrogen Peroxide Addition	Has been demonstrated at full scale. Issues of fluid flow, oxygen transport, aquifer clogging
		In situ	Has been demonstrated at full scale
		Instrinsic Bioremediation	No technology involved, but would benefit from improved evaluation
		Landfarming	Full scale
		Nitrate Enhancement	Pilot scale demonstrations. Issues of end products and scale up.
Energetics	High	Bioreactors	Full scale for hydrocarbons. Transition from pilot to full scale for energetics
		Composting	Field demonstrations successful
		In situ	Pilot scale successes
		Microbial Mats	Laboratory successes. Need pilot and field demonstrations for validation
		Phytoremediation/ Constructed Wetlands	Some scaled up batch demonstrations. Primarily laboratory scale.
		White Rot Fungus	Pilot scale. Issues of competition, toxicity, sorption and cleanup levels
Halogenated Hydrocarbons	High	Aerobic Cometabolism	Lab scale. Requires basic understanding
		Anaerobic/Aerobic Sequencing	Demonstrated in *ex situ* reactors. Requires procedures for achieving *in situ* sequencing.
Metals	High	Bioaccumulation	Commercial scale
		Biobeneficiation	Used commercially in mining
		Bioleaching	Used commercially in mining
		Constructed Wetlands	Demonstrated at pilot scale. Full scale demonstration planned
		Methylation	Laboratory scale
		Microbial Mats	Lab and bench scale. Needs investigation of intermediates, ultimate fate of contaminants.
		Redox Reactions	Bench scale. Needs pilot demonstrations
		Vegetative Uptake	Bench scale. Needs transition from isolated cell groups to intact plants

cometabolic aerobic degradation has been demonstrated in *ex situ* bioreactors. However, routine procedures for implementing this sequence *in situ* have not yet been established at the commercial scale. Obstacles for implementing this technology for *in situ* use include transport of electron donors and acceptors to the contaminant, transport of a primary substrate to the microorganisms, and attaining complete mineralization. The prevalence of chlorinated solvent contamination and the expense of alternative pump-and-treat methods make this technology worthy of development.

Constructed wetlands. Constructed wetlands contain robust consortia of living organisms that involve higher plant species as well as microbes. Constructed wetlands have the ability to treat a variety of contaminants simultaneously. This technology has been demonstrated at the pilot scale, and a full-scale demonstration is planned under the EPA SITE program. If the time scale of these tests is favorable, the results should be examined closely to determine if further demonstrations are warranted. Engineering of optimal conditions may require additional field trials.

White rot fungus. The ability of white rot fungus to treat some contaminants has been known for 10–15 years. White rot fungus has successfully degraded TNT in pure aqueous cultures in many laboratory and pilot scale tests. In addition, the results of laboratory and pilot scale demonstrations have shown the potential for white rot fungus to degrade not only nitroaromatics (TNT) and nitramines (RDX and HMX), but other difficult to degrade materials such as DDT, PAHs, PCBs and PCP as well. Nevertheless, there are a number of obstacles that limit the use of this technology at the commercial scale. These include competition from native bacteria, toxicity of contaminants to the fungus, chemical sorption, and engineering the fungal treatment to meet desired cleanup levels. Further, for all applications, questions remain about the ultimate fate of the contaminants and intermediates. In the many years of testing on white rot fungal systems, field-level experiments have failed to acheive the performance demonstrated in the laboratory. Thus, we recommend that any proposed field-level demonstration that utilizes white rot fungus be examined for evidence of scientific or engineering breakthroughs that might improve the likelihood of success at the field scale. In light of the potential for white rot fungus to degrade many refractory contaminants, we are reluctant to dismiss it entirely; however, without significant improvements in the process, a field-scale demonstration using white rot fungus is likely to fail.

Beyond our primary recommendations, we make note of two other technologies of interest: microbial mats and systems capable of assessing and monitoring bioremediation activities.

Microbial mats. Microbial mats, like constructed wetlands, contain complex consortia of aerobic and anaerobic bacteria that have shown the potential to treat a variety of contaminants, including energetics, heavy metals and polycyclic aromatic hydrocarbons. Laboratory demonstrations have shown depletion of energetics greater than 99 percent in a matter of days. Treatment of metals using microbial mats is less mature, but controlled experiments have shown decreases in metal concentrations of 80–90 percent, with initial concentrations that would be toxic to many microbial systems. The ultimate fate of products, particularly metals that are isolated rather than mineralized, the implications of adsorption rather than degradation of contaminants, and the creation of intermediates are issues that must be addressed before the technology can be brought to full scale. Although demonstrations of microbial mat treatments have been limited to the laboratory, the potential for treating a variety of contaminants simultaneously may justify investment in larger demonstrations. However, investment in this less mature technology at the full-scale level carries a high risk of failure. Therefore, additional testing at the pilot scale is encouraged.

Evaluation and monitoring technologies. Many bioremediation technologies suffer from the lack of adequate systems for evaluating and monitoring relevant parameters. As such, it is often difficult to determine whether the biological system is responsible for the contaminant degradation or containment. The development of systems for monitoring or assessing the status of biological treatment systems is needed for all bioremediation applications. This need is particularly acute if intrinsic bioremediation is to be advanced as an alternative.

The decision to invest DoD resources in the technologies likely to benefit from field-level demonstrations should also consider (1) the priority assigned to the problem by the services and the extent of the problem within DoD and (2) the extent of the problem outside DoD and the accompanying likelihood that other sources will supply the necessary resources for technology validation. In considering the first factor, the service-identified priorities favor investment in chlorinated hydrocarbon and metals remediation techniques. Further, the prevalence of chlorinated hydrocarbon contamination, both for DoD and the private sector, demands that remediation techniques for this problem be given serious consideration for investment. However, both chlorinated compounds and metals contamination are shared by DoD and the private sector, and currently are receiving substantial

non-DoD attention. The demonstrations listed in the appendix show that there is substantial non-DoD investment in bioremediation strategies for the treatment of halogenated and non-halogenated hydrocarbons and PAHs. There is considerably less investment in treatment technologies for metals and energetics.

Thus, considering the state of the technology, its applicability to DoD contamination, and the relative investment in the various technologies from external funding sources, we recommend the following technologies for field demonstrations:

- bioreactors for treatment of energetics
- anaerobic/aerobic sequencing for chlorinated compounds
- constructed wetlands
- white rot fungus (with caveats).

In addition, microbial mats, for the simultaneous treatment of multiple contaminants, should be considered for smaller pilot scale tests, and there is a general need for systems for monitoring and evaluating bioremediation processes.

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GLOSSARY

BAP	benzoaminophenol
BTEX	benzene, toluene, ethylbenzene, and xylenes
DCE	1,1-dichloroethylene
DDT	dichlorodiphenyltrichloroethane
DNAPL	dense non-aqueous phase liquid
DNB	dinitrobenzene
DNT	dinitrotoluene
DoD	Department of Defense
DoE	Department of Energy
EDTA	ethylenediaminetetraacetic acid
EPA	Environmental Protection Agency
GAC	granular activated carbon
GEM	genetically-engineered microbes
HDPE	high density polyethylene
HMX	octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazcine
LNAPL	light non-aqueous phase liquid
MCPA	methylchlorophenoxyacetic acid
NAPL	non-aqueous phase liquid
PACT	powdered activated carbon treatment
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PCE	per- or tetrachloroethylene
PCP	pentachlorophenol
POL	petroleum, oils, lubricants
POTW	potable water
RCRA	Resource Conservation and Recovery Act
RD/RA	Remedial Design/Remedial Action
RDX	hexahydro-1,3,5-trinitro-1,3,5-triazine
ROD	Record of Decision
SITE	Superfund Innovative Technology Evaluation

SVOC	semi-volatile organic compound
TCE	trichloroethylene
TNB	1,3,5-trinitrobenzene
TNT	2,4,6-trinitrotoluene
TOC	total organic carbon
TPH	total petroleum hydrocarbon
USAEC	U.S. Army Environmental Center
UV	ultraviolet
VC	vinyl chloride
VOC	volatile organic compound

APPENDIX A

SUMMARY OF BIOREMEDIATION DEMONSTRATIONS DOCUMENTED IN THE *EPA BIOREMEDIATION IN THE FIELD SEARCH SYSTEM* AUGUST 1994

APPENDIX A
SUMMARY OF BIOREMEDIATION DEMONSTRATIONS DOCUMENTED IN THE *EPA BIOREMEDIATION IN THE FIELD SEARCH SYSTEM* AUGUST 1994

The table below shows the number of publicly and privately funded bioremediation demonstrations that treat each of the various contaminants classes discussed in this report. The numbers are based on projects listed in the *Bioremediation in the Field Search System*, August 1994. Sites with more than one type of contaminant class are counted once in each of the classes. For example, many of the sites contaminated with petroleum hydrocarbons also contain heavy metals. If the bioremediation demonstration is aimed at treating the hydrocarbons, but not the metals, it is included in the tabulation of hydrocarbon demonstrations only. If, however, the bioremediation demonstration is to address both the hydrocarbons *and* the metals, it is counted once in each category. A short description of each project follows.

Contaminant	Number Of Demonstrations	Page
Non-halogenated hydrocarbons	99	A-5
Energetics	1	A-19
PAHs	47	A-21
Halogenated hydrocarbons	66	A-25
Inorganic (non-metal)	2	A-31
Metals	3	A-33
Mixed	74	A-35

NON-HALOGENATED HYDROCARBONS

(1) Charles George Landfill, Tyngsboro, MA, landfill

STATUS: Predesign

TREATMENT SUMMARY: *Ex situ* treatment, activated sludge, completely mixed flow. Aerobic conditions, exogenous organisms. Nonbiological technologies: activated sludge for leachate, preaeration, carbon filtering.

MEDIA AND CONTAMINANTS: Ground water contaminated with BTEX, solvents, and arsenic

(2) FAA Technical Center—Area D, Atlantic County

STATUS: Full-scale remediation is planned. Currently being installed. Pilot-scale studies have been completed.

The ROD was signed in 1989, and the design has been approved since 1992. However, there have been delays in the implementation of full-scale bioremediation.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation, *in situ* soil bioremediation (*in situ* land treatment). Nutrient addition. Treatment train includes free product extraction, bioremediation, and soil venting. Both soil and ground water are being treated *in situ* at the same time through the same process.

MEDIA AND CONTAMINANTS: Saturated soil with BTEX and jet fuel. Ground water with NAPLs.

(3) Knispel Construction Site, Horseheads

STATUS: Full-scale remediation was completed 10/89. Started 01/89. Laboratory-scale studies have been completed. Incurred cost: $250K.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation, *in situ* soil bioremediation (*in situ* land treatment). Hydrogen peroxide, nutrient addition (RESTORE 375). Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Soil and ground water contaminated with petroleum.

(4) Nascolite, Millville, abandonded manufacturing facility

STATUS: Full-scale remediation is planned. Currently in design. Laboratory-scale studies were completed 06/92. Started 04/92. Pilot-scale studies were completed 06/94. Started 02/93.

TREATMENT SUMMARY: *Ex situ* treatment, fluidized bed, plug flow. Aerobic conditions, indigenous organisms. Nonbiological technologies: filtration.

MEDIA AND CONTAMINANTS: Ground water contaminated with methylmethacrylate and other volatile and semivolatile organics

(5) American Linen, Stillwater, Cleaning industry

STATUS: Full-scale remediation was completed 08/92. Started 07/91.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. 60 ft by 270 ft treatment cell with impervious bottom liner. Aeration provided by tilling soil.

MEDIA AND CONTAMINANTS: Soil contaminated with BTEX, lube oil, PAHs, VOCs

(6) Mobil Terminal, Buffalo, NY, oil storage facility

STATUS: Full-scale remediation has been underway since 07/91. Laboratory-scale and pilot-scale studies have been completed. In this ongoing process, treated soil remains on site at Mobil Terminal. An air extraction system was installed in summer 1991 to enhance bioremediation in part of the biocell.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, exogenous and indigenous organisms. Nonbiological technologies: vacuum extraction. Treatment involves two bioremediation processes: 50% of site is undergoing soil tilling and 50% of site is undergoing soil tilling and air extraction.

MEDIA AND CONTAMINANTS: Soil contaminated with diesel and gasoline

(7) Osmose, Buffalo, NY, parking lot at a wood preserving facitlity

STATUS: Full-scale remediation has been underway since 09/90. Total expected cost: $125K. LNAPLs were found in some areas of the biocell, and PAHs in these areas have not been affected by the bioremediation. LNAPLs recovery and bioremediation are still being performed. Bioremediation is not going in preferred direction. Non-biological treatment technologies, such as ozone injections, are also being considered as an alternative.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. A bioremediation cell was made, lined with an HDPE liner. Contaminated soil was placed in cell. Air and nutrients were supplied through perforated pipes. A parking lot was built over the top of it, and samples are taken at regular intervals.

MEDIA AND CONTAMINANTS: Vadose and saturated soil contaminated with BAP, PAHs. Soil contaminated with BTEX, fuel oil, and creosote

(8) Plattsburgh Air Force Base, Plattsburgh, NY, fire training area

STATUS: Full-scale remediation is planned. Currently in predesign. Pilot-scale studies were completed 02/94. Started 01/93. Air permits are being considered by New York State.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms. An approximately 3.5 hp blower is used for one or two vent wells, and there are three monitoring points per vent well. Air emissions from the contaminated soil are a concern of New York State Department of Environmental Conservation. A flux box was used to measure surface emissions and the results showed that contamination was not being emitted from the site.

MEDIA AND CONTAMINANTS: Ground water contaminated with BTEX free product.

(9) Syracuse, Syracuse, NY, underground petroleum tanks

STATUS: Full-scale remediation was completed 10/91. Started 07/90.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS Soil contaminted with petroleum

(10) Dover Air Force Base, Dover, DE, fueling system leaks

PROCESS 1 STATUS: Full-scale remediation is planned. Pilot-scale studies have been underway since 11/92. Total expected cost: $180K. Site has experienced problems with free product and ground water contamination.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms. Nonbiological technologies: vacuum extraction, air sparging. A study was carried out to see if natural attenuation is checking the migration of dissolved contamination.

MEDIA AND CONTAMINANTS: Vadose soil with BTEX and TPHs. Ground water with BTEX

PROCESS 2 STATUS: Full-scale remediation is planned. Currently in predesign. Pilot-scale studies have been underway since 01/93. Site has solvents in ground water, and high iron and manganese.

TREATMENT SUMMARY: *In situ* treatment, air sparging. Aerobic conditions, indigenous organisms. Nonbiological technologies: vacuum extraction. Air is injected into the base of the unconfined aquifer. Soil burrowing is done beforehand to make sure that the pattern of sparged air is not altered.

MEDIA AND CONTAMINANTS: Soil and ground water contaminated with solvents

PROCESS 3 STATUS: Pilot-scale studies are planned.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with BTEX, PAHs, TCE, TPHs

PROCESS 4 STATUS: Full-scale bioremediation is not planned. Pilot-scale studies are planned. Incurred cost: O&M, $100K. Total expected cost: capital, $1.2M. Because of contracting problems, this never got off the ground. Further tests may be conducted.

TREATMENT SUMMARY: *In situ* treatment, bioventing. *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Nonbiological technologies: vacuum extraction, asphalt binding (probably not going to be used).

MEDIA AND CONTAMINANTS: Vadose soil contaminated with BTEX, TPHs

(11) Autostyle, Kentwood, MI, leaking underground storage tank

STATUS: Full-scale remediation has been underway since 09/90. Laboratory-scale and pilot-scale studies have been completed.

TREATMENT SUMMARY: *Ex situ* treatment, fixed film, completely mixed flow. Aerobic conditions. Nonbiological technologies: vacuum extraction, soil vapor extraction for product recovery and soil treatment. Treatment is an aerobic attached growth process involving a submerged, fixed-film bioreactor.

MEDIA AND CONTAMINANTS: Ground water contaminated with alcohol, aromatic ketones

(12) K.I. Sawyer Air Force Base, Marquette, MI, petroleum storage ares and inactive firefighter training area

PROCESS 1 STATUS: Full-scale remediation is planned. Currently in predesign. Pilot-scale studies have been completed. Site is located in northern U.S., near Lake Superior. Accumulation of snow and freezing temperatures for more than 6 months of the year make field work and system operation difficult.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms. Nonbiological technologies: a 12-week study was conducted from November 1990 to February 1991 to evaluate the effectiveness of dual pump versus single pump hydrocarbon recovery for free product on the water table.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with benzene, toluene, xylene

PROCESS 2 STATUS: Full-scale remediation is planned. Currently in predesign. Pilot-scale studies are being conducted. Site is located in northern U.S., near Lake Superior. Accumulation of snow and freezing temperatures for more than 6 months of the year make field work and system operation difficult.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with benzene, toluene, xylene

(13) Mayville Fire Department, Mayville, MI, leaking underground storage tank

STATUS: Full-scale remediation has been underway since 05/90. Expected completion 12/94. Incurred costs: capital, $12K; O&M, $4,000. Non-detectable levels have been achieved. However, the project has not yet been closed out. Cleanup appears to be complete, but monitoring needs to occur for three more quarters.

TREATMENT SUMMARY: *In situ* treatment, air sparging. Aerobic conditions, indigenous organisms. Treatment involves air sparging in a closed-loop system: ambient air is injected into the water to increase dissolved oxygen and enhance naturally occurring biodegradation.

MEDIA AND CONTAMINANTS: Ground water contaminated with benzene, ethylbenzene, toluene, xylenes

(14) Rasmussen, Livingston County, MI

STATUS: Predesign.

TREATMENT SUMMARY: *Ex situ* treatment, fixed film. Exogenous organisms. Nonbiological technologies: chemical treatment, air stripping/carbon adsorption with nutrient addition. Site is considering pump and treat air stripping/carbon adsorption treatment with added micro-organisms and nutrients using a fixed-film reactor.

MEDIA AND CONTAMINANTS: Ground water contaminated with solvents (2-butanone, 4-methyl-2-pentanone, acetone)

(15) Sleeping Bear Dunes National Lakeshore, Empire, MI
STATUS: Predesign.
TREATMENT SUMMARY: Anaerobic conditions, indigenous organisms.
MEDIA AND CONTAMINANTS: Ground water contaminated with petroleum

(16) Speigelberg Landfill, Livingston Township, MI
STATUS: Predesign.
TREATMENT SUMMARY: Exogenous organisms. Nonbiological technologies: air stripping/carbon adsorption with nutrient addition. Pump and treat, air stripping/carbon adsorption treatment with added microorganisms and nutrients.
MEDIA AND CONTAMINANTS: Ground water contaminated with solvents (2-butanone, hexanone)

(17) Upjohn Company Portage Facility, Kalamazoo, MI, chemical manufacturing facility
STATUS: Full-scale remediation is planned. Currently in predesign. Pilot-scale studies have been underway since 01/87. Site anticipates possible problems with low winter temperatures.
TREATMENT SUMMARY: *Ex situ* treatment, fixed film, non-aerated lagoon, completely mixed flow. Aerobic conditions, indigenous organisms. Nonbiological technologies: *in situ* soil flushing, vacuum extraction. Bioreactors are cylindrical, 10 to 20 feet tall, and up to 12 feet in diameter. Air is provided by blowers distributed throughout the reactors. Chemical feed lines add nutrients to enhance biodegradation. The non-aerated lagoon is a place where the company disposes its wastewater. The company claims that there are no hazardous waste compounds in the wastewater, and that the wastewater undergoes natural degradation.
MEDIA AND CONTAMINANTS: Soil and ground water contaminated with solvents

(18) B&F Trucking Company, Rochester, MN, leaking underground storage tank
STATUS: Full-scale remediation was completed 12/92. Started 04/91. Laboratory-scale studies were completed 01/90. Pilot-scale studies have been completed. Incurred cost: $341K. The aboveground bioreactor portion of the process went well; however, there were problems with the reinfiltration step, due to water levels. The upgradient infiltration gallery was periodically swamped by rising ground water level, so the treated water could not be infiltrated. Increase in the iron concentration in ground water caused iron bacteria and resulting "slime" to accumulate on the surface of pipes and other process equipment. Site now has converted to nonbiological process.
TREATMENT SUMMARY: *Ex situ* treatment, sequencing batch reactor, completely mixed flow. Aerobic conditions, indigenous organisms. Ground water is collected in three recovery wells and pumped to a separator tank where free product is separated from the dissolved phase. Effluent then is treated in an aboveground bioreactor. The treated effluent is reinfiltrated into the ground upgradient of the release area and recovery wells.
MEDIA AND CONTAMINANTS: Soil and ground water contaminated with BTEX lube oil

(19) Kenworth Truck Company, Chillicothe, OH, leaking underground storage tank and truck manufacturing area
STATUS: Full-scale remediation has been underway since 03/94.
TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. *Ex situ* treatment, GAC bioreactor. Hydrogen peroxide, nutrient addition (nitrogen, phosphorus), completely mixed flow. Aerobic conditions, indigenous organisms. GAC bioreactor is used to pretreat ground water, which then is amended with nitrogen and phosphorus and injected into the subsurface to deliver nutrients to the aquifer/small volume soils.
MEDIA AND CONTAMINANTS: Vadose soil contaminated with TPHs. Ground water contaminated with benzene, ethylbenzene, acetone, toluene, xylene

(20) Newark Air Force Base, Newark, OH, spillage from active underground storage tanks.

STATUS: Full-scale bioremediation is not planned. Pilot-scale studies were completed 12/93. Started 08/92. Incurred costs: capital, $35K; O&M, $1,000. Total expected costs: capital, $35K; O&M, $2,000. The remediation involves small, localized areas of petroleum product contamination; therefore, the treatability study may accomplish complete remediation of the site. Most of the areas were below the state's action levels initially. Informal policies placed the TPH standard at an arbitrary 100 mg/kg; very infeasible and subject to false positives and organic interference. By targeting small, localized areas, bioventing could accomplish remediation to the risk-based levels enacted shortly after reporting this site. In addition, facility upgrade projects would remove residual contamination.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contamination with gasoline, TPHs

(21) Wright-Patterson Air Force Base, Dayton, OH

STATUS: Pilot-scale studies have been underway since 07/93.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms. Treatment involves bioventing using air injection at a single vent well.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with BTEX jet fuel

(22) Old Inger, Darrow, LA, inactive waste oil recycler

STATUS: Full-scale remediation is being conducted. Laboratory-scale studies have been completed. Pilot-scale studies were completed 11/86. Started 10/85. Incurred cost: $5.4M. Total expected cost: $12.5M. No problems with bioremediation. Full-scale operations were delayed due to state lag time in procuring contractor.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Nonbiological technologies: granular activated carbon for water treatment. Solid-phase bioremediation is used.

MEDIA AND CONTAMINANTS: Sludge contaminated with hydrocarbons. Soil contaminated with petroleum. Metals may remain, but they are not expected to be above health-based levels.

(23) Atchinson - ATSS Santa Fe Lake, Santa Fe, NM, contaminated plaza lake

STATUS: Full-scale remediation has been underway since 07/92. Pilot-scale studies have been completed. Total expected cost: $10M. There is a possible problem with high chloride content in soil and sludges.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). *Ex situ* land treatment. Nutrient addition. Aerobic conditions, indigenous organisms. The treatment consists of *in situ* and combined bioprocesses: surface and subsurface sediments are treated separately. Sediments in the middle of the lake are applied to remediated soils and undergo biotreatment on the outer edge of the lake. Soils on the outer edge of the lake are bioremediated *in situ.*

MEDIA AND CONTAMINANTS: Sediments contaminated with diesel. Soil contaminated with hydrocarbons. Chlorides (unspecified) are also present.

(24) Matagora Island Air Force Range, Matagora Island, TX, former Air Force bombing range with JP-5 storage tanks

STATUS: Full-scale remediation was completed 03/93. Incurred cost: capital, $77.9K. Bioremediation proved successful in cleaning up the site to below the necessary levels. The site is now in the process of being closed to further remedial action.

TREATMENT SUMMARY: *Ex situ* treatment, pile, addition of Pseudomonas microbial slurry. Aerobic conditions, exogenous organisms. Contaminated soil was excavated and spread in 9-inch layers on a concrete surface, and a Pseudomonas microbial slurry was applied. The soil then

was mixed and tested for BTEX compounds and TPH. The process was repeated as necessary until contamination was reduced to below Texas Water Commission Requirements.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with BTEX jet fuel, benzene, ethylbenzene, toluene, TPHs, xylene

(25) Park City, Park City, KS, leaking underground pipe

STATUS: Full-scale remediation has been underway since 06/93. Laboratory-scale studies were completed 01/93. Started 01/92. Incurred cost: $275K. Total expected cost: $650K. Site is serving as a test case for new Kansas environmental regulations.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation, *in situ* sediment bioremediation. Nutrient addition (nitrate is added as an electron receptor). Aerobic and anaerobic conditions, indigenous organisms. Nitrate serves as an alternate electron receptor for the microbial metabolism of the BTEX component of the hydrocarbon in the spill. The effort is focused on the remediation of regulated components.

The migration of contaminants is an issue. It has been dealt with by establishing a purge well going to an air stripper which discharges in the surface water. This is operating in the capture zone of the purge well.

MEDIA AND CONTAMINANTS: Ground water contaminated with benzene, m-xylene, ethylbenzene, o-xylene, p-xylene, toluene. Long-chain, high molecular weight alkenes are also present.

(26) Public Service Company, Denver, CO, Subsurface petroleum spill caused by leaking catch basin for used automotive oil

PROCESS 1 STATUS: Full-scale remediation was completed 03/92. Started 06/89. Incurred cost: $500K. A risk assessment has been submitted to the State of Colorado Health Department for review. The State has accepted the closure application for the site.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation, combined bioprocess. Hydrogen peroxide, nutrient addition (ammonium and phosphate compounds). Aerobic conditions, indigenous organisms. Nonbiological technologies: chemical treatment. The indigenous aerobes were cultivated using hydrogen peroxide and nutrients injected into the subsurface. Nothing is added to the soil. Treatment occurred in several stages. First, ground water was pumped from a recovery well downgradient of the leaking tank at a rate of 11 gpm. The recovered water was then treated by carbon adsorption to remove the dissolved hydrocarbons before being pumped to a nutrient gallery. In the nutrient gallery, the ground water was amended twice: first with ammonium and phosphate compounds to provide inorganic nutrients; then with hydrogen peroxide to increase the water's level of dissolved oxygen. The amended ground water was then reinjected upgradient of the leaking tank, thereby delivering the nutrients and oxygen needed to sustain aerobic biodegradation in the saturated zone.

MEDIA AND CONTAMINANTS: Ground water contaminated with benzene, toluene, xylene

PROCESS 2 STATUS: Full-scale remediation has been completed.

TREATMENT SUMMARY: *In situ* treatment, bioventing, *in situ* ground water bioremediation, *in situ* sediment bioremediation. Oxygen source, nutrient addition. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Sediments contaminated with ethylbenzene, toluene, xylene

(27) Burlington Northern, Glendive, MT, petroleum contaminated landfarm

STATUS: Full-scale remediation has been underway since 01/91.

TREATMENT SUMMARY: *Ex situ* land treatment, active tillage, nutrient control. Aerobic conditions, indigenous organisms. Land treatment involves active tillage (once per month), moisture control, and seasonal monitoring of contaminants. Below treatment zone monitoring is conducted once per year for leaching.

MEDIA AND CONTAMINANTS: Soil contaminated with diesel

(28) Glasgow Former Air Force Base, Glasgow, MT

STATUS: Full-scale remediation is planned. Expected start 07/95. Total expected costs: capital, \$2,000; O&M, \$1,000. The cold weather of northern Montana might pose an obstacle to effective landfarming. State is sensitive about the total volume of material to be landfarmed.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Contaminated soil from UST removal operations will be placed within a bermed area in a layer not greater than 6 inches. Contaminated soil will be segregated into two areas: one for soil contaminated with gasoline and aviation fuels, and the other for soil contaminated with all other types of petroleum. The landfarm will be maintained for 1 year after the placement of the soil. Soil will be tilled mechanically to the full depth at least eight times (approximately monthly from May to October) to increase exposure to air and sunlight.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with BTEX, TPHs

(29) Montana Rail Link—East Helena, East Helena, MT, petroleum contaminated landfarm

STATUS: Full-scale remediation has been underway since 05/92.

TREATMENT SUMMARY: *Ex situ* land treatment, tillage, moisture and nutrient control. Aerobic conditions, indigenous organisms. Process involves active tillage once per month, moisture and nutrient control, seasonal monitoring, and monitoring below treatment zone.

MEDIA AND CONTAMINANTS: Soil contaminated with diesel

(30) Montana Rail Link—Missoula, Missoula, MT, petroleum contaminated landfarm

STATUS: Full-scale remediation has been underway since 05/92.

TREATMENT SUMMARY: *Ex situ* land treatment, tillage, moisture and nutrient control. Aerobic conditions, indigenous organisms. Process involves active tillage once a month, May through October, and moisture and nutrient control.

MEDIA AND CONTAMINANTS: Soil contaminated with petroleum

(31) Hill Air Force Base, Salt Lake City, UT, tool maintenance building, engine storage yard, fuel storage yard

STATUS: Full-scale remediation has been underway since 09/91. If Hill AFB can get funding, bioventing could be conducted on soils with different contaminant mixtures: (1) gasoline and chlorinated solvents, and (2) petroleum hydrocarbons, JP-4 jet fuel, dioxins/furans, and solvents.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Oxygen source. Aerobic conditions, indigenous organisms. Nonbiological technologies: vapor venting. Combination of bioremediation and vapor venting is used.

MEDIA AND CONTAMINANTS: Soil and ground water contaminated with TPHs

(32) Aua Fuel Farm, American Samoa, leaking above ground storage tanks at former Nave fuel farm

STATUS: Full-scale remediation has been underway since 12/93. Expected completion 12/95. Pilot-scale studies were completed 01/92. Incurred costs: capital, \$700K; O&M, \$10K.

TREATMENT SUMMARY: *In situ* treatment, delivery of dissolved oxygen. Nutrient addition (soils (nitrogen, phosphorus). Aerobic conditions, indigenous organisms. The existing water supply is used to deliver oxygen and nutrients to contaminated subsurface regions at flow rates designed to stimulate *in situ* biodegradation of diesel fuel dissolved in ground water and sorbed to soil particle surfaces. Water is delivered to the soil through shallow trench systems, which operate as leach field systems. Each trench system is connected to a remedial system that increases the concentration of nutrients and oxygen in the applied water. Because the site is located in an isolated area, the remedial design is simple and completely passive. Gravity is

used to deliver the water to the soil. The system has no moving parts and thus is essentially maintenance free.

MEDIA AND CONTAMINANTS: Soil contaminated with diesel

(33) Beale Air Force Base, Marysville, CA

PROCESS 1 STATUS: Full-scale remediation has been underway since 07/92. Pilot-scale studies were completed 12/91. Started 10/91. Incurred cost: capital, $30K. Total expected cost: O&M, $6,000. Pilot-scale test demonstrated that bioremediation could work in silty-clay soil.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with diesel

PROCESS 2 STATUS: Pilot-scale studies have been underway since 10/92. Total expected costs: capital, $50K; O&M, $10K. Project will be a pilot-scale system, operating for one year.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with diesel, gasoline, solvents

PROCESS 3 STATUS: Pilot-scale studies have been underway since 10/92. Total expected costs: capital, $50K; O&M, $10K. Project will be a pilot-scale test for one year.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with diesel, gasoline

PROCESS 4 STATUS: Full-scale remediation has been underway since 11/92. Total expected costs: capital, $100K; O&M, $30K. Biofilters to treat contaminated soil were removed during Underground Storage Tank removal projects.

TREATMENT SUMMARY: *Ex situ* treatment, pile. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with diesel, gasoline

PROCESS 5 STATUS: Pilot-scale studies have been underway since 10/92. Total expected costs: capital, $50K; O&M, $10K. Pilot-scale system to operate for one year.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with benzene, diesel, ethylbenzene, toluene, xylene. Lead is also present.

PROCESS 6 STATUS: Full-scale remediation is planned. Currently in design. Remediation expected completion 06/96. Total expected costs: capital, $221K; O&M, $64K.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with diesel, gasoline, TCE. Lead is also present.

PROCESS 7 STATUS: Full-scale remediation is planned. Currently in design. Remediation expected completion 10/96. Total expected costs: capital, $30K; O&M, $6,000. Process area recently was discovered; little information is available.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with benzene, diesel, ethylbenzene, toluene, xylene. Lead is also present.

(34) CALTRANS, Lakeport, CA

STATUS: Full-scale remediation was completed 01/89. Started 11/88. Degradation rate was dependent upon the pile's porosity, water content, type of waste, soil, and bacterial consortium. Additional information on this site can be obtained through the California Department of Toxic Substances Control, Office of Pollution Prevention and Technology Development.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Nonbiological technologies: passive aeration. Bioremediation was used at two sites: at one site, a single pile was treated with an aqueous nutrient solution and passive aeration; at the second site, one pile was treated with an aqueous nutrient solution and active aeration while a second pile was used as a control.

MEDIA AND CONTAMINANTS: Soil contaminated with hydrocarbons

(35) CWX Freight Lines, Santa Rosa, CA, leaking underground storage tank

STATUS: Full-scale remediation was completed 11/91. Started 10/90. Pilot-scale studies have been completed.

TREATMENT SUMMARY: *Ex situ* land treatment. Nutrient addition (Solmar L-104, 32-10-10 fertilizer). Aerobic conditions, exogenous organisms. Soil was excavated and placed on a liner. A sprinkler system was installed to apply moisture when required. Solmar L-104 and fertilizer (32-10-10) were added to enhance biodegradation.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with diesel

(36) Citrus Heights Irrigation, Citrus Heights, CA

STATUS: Full-scale remediation was completed 08/89. Started 05/89.

TREATMENT SUMMARY: *Ex situ* treatment, leachate recirculation, completely mixed flow. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Soil contaminated with diesel

(37) Converse/Montebello Corporation Yard, Montebello, CA, leaky tanks

STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies have been completed. Pilot-scale studies have been underway since 05/93. Results of pilot-scale will be considered when developing a full-scale system; the benefits of nutrient addition will be evaluated against bioventing without nutrient addition.

TREATMENT SUMMARY: *In situ* treatment, bioventing, bioventing and bioremediation augmentation. Nutrient addition (soils (nitrate and phosphate)). Aerobic conditions, indigenous organisms. Nonbiological technologies: vacuum extraction. Bioventing augmented through addition of nutrients to enhance bioremediation.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with diesel, gasoline

(38) Former Service Station, Los Angeles, CA, leaking underground storage tanks

STATUS: Full-scale remediation was completed 03/91. Started 11/88. Pilot-scale studies were completed 12/88. Started 01/88. Incurred cost: $1.6M. During channeling, overload reduced the reinjection process rate.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation, closed loop system. Hydrogen peroxide, nutrient addition (nitrogen and others). Aerobic conditions, indigenous organisms. Nonbiological technologies: *in situ* soil flushing, vacuum extraction. Ground water extraction, treatment, and reinjection.

MEDIA AND CONTAMINANTS: Soil contaminated with hydrocarbons. Ground water contaminated with benzene

(39) MCAGCC Twenty-Nine Palms, Twenty-Nine Palms, CA. There are 20 different sites under this heading. Many of them are leaking underground storage tanks. There are others which are a unique military variant of the tanks: up to 20,000 gallon rubber fuel bladders which can have leakage problems.

PROCESS 1 STATUS: Full-scale remediation is planned. Currently in design. Pilot-scale studies have been underway since 01/94. Expected completion 01/97. There have been problems with acceptance of bioremediation technology.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms. Nonbiological technologies: some of the bioventing sites are irrigated with water. Treatment involves an aboveground bioremediation system over a liner with leachate collection and induced air infiltration systems.

MEDIA AND CONTAMINANTS: Soil contaminated with gasoline, JP-5

PROCESS 2 STATUS: Pilot-scale studies have been underway since 01/94.

TREATMENT SUMMARY: *In situ* treatment, *in situ* natural aspiration of wells. Aerobic conditions, indigenous organisms. Natural aspiration is occurring in some of the wells in sandy sands.

The wells tend to breathe by themselves. This phenomenon is not yet understood, but has been observed in other places as well and can be used for bioremediation purposes. Vapor emissions are a potential problem, but are guarded against by the use of seals or one-way valves.

MEDIA AND CONTAMINANTS: Soil contaminated with gasoline, JP-5 jet fuel

(40) Naval Weapons Station—Seal Beach, Seal Beach, CA, contamination from leaking underground storage tanks, which have now been removed.

STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies have been completed. Pilot-scale studies have been underway since 12/92. Expected completion 12/95. Benzene is most recalcitrant, however; only after 100 days acclimation period does it degrade.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. Nutrient addition. Aerobic and anaerobic conditions, indigenous organisms. A gallery of injection and monitoring wells has been established at the site. Nutrients are circulated through the zone of contamination (via the wells). Bioremediation is monitored through weekly sampling of the ground water.

MEDIA AND CONTAMINANTS: Ground water contaminated with BTEX.

(41) Oakland Chinatown, Oakland, CA

STATUS: Full-scale remediation was completed 08/90. Started 03/89. Laboratory-scale studies were completed 01/89. Started 10/88. Incurred costs: capital, $300K; O&M, $480K. Total expected cost: O&M, $1.2M. Cost per year: O&M, $720K. Site has been closed since 1990 and a plaza has been built in its place.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation, *in situ* soil bioremediation (*in situ* land treatment). *Ex situ* treatment, completely mixed reactor. Hydrogen peroxide, nutrient addition [soils and water (ammonia nitrate, mono- and di-basic phosphates)], completely mixed flow. Aerobic conditions, indigenous organisms. Nonbiological technologies: carbon adsorption. *In situ* bioremediation involved ground water extraction and reinjection in a closed loop system. Nutrients and hydrogen peroxide were added to the ground water prior to reinjection. Residual contamination in ground water was treated in a bioreactor supplemented by carbon adsorption.

MEDIA AND CONTAMINANTS: Soil and ground water contaminated with BTEX, TPHs

(42) Protek, Carson City, CA

STATUS: Full-scale remediation was completed 12/89. Started 08/88. The control cell, which did not receive any nutrient supplements, proprietary inoculum, or the benefit of rigorous aeration, showed contaminant level reductions equal to those of the treatment cells. Additional information on this site can be obtained through the California Department of Toxic Substances Control, Office of Pollution and Prevention and Technology Development.

TREATMENT SUMMARY: *Ex situ* land treatment. Diesel fuel-contaminated soil was biologically treated above ground in treatment cells.

MEDIA AND CONTAMINANTS: Soil contaminated with TPHs

(43) SEGS Solar Project, Kramer Junction, CA, solar energy generating station

STATUS: Full-scale remediation has been underway since 07/90. Laboratory-scale studies have been completed. Pilot-scale studies were completed 01/90. Full-scale treatment is used on an ongoing basis for treatment of soil contaminated by occasional leaks and spills.

TREATMENT SUMMARY: *Ex situ* treatment, pile. Aerobic conditions, indigenous organisms. Soil treated in piles by addition of water and nutrients and occasional tillings.

MEDIA AND CONTAMINANTS: Soil contaminated with biphenyl, diphenyl ether

(44) San Diego Gas and Electric, San Diego, CA, leaky tank

STATUS: Full-scale remediation was completed 04/93. Started 10/89. Incurred cost: capital, \$25K. Cost per year: O&M, \$12.5K.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation, *in situ* soil bioremediation (*in situ* land treatment). Nutrient addition (NO3, PO4, K+). Anaerobic conditions, indigenous organisms. Infiltration of nutrient-laden water followed by extraction as ground water that is recirculated (reinfiltrated) to form a "closed-loop" system.

MEDIA AND CONTAMINANTS: Soil contaminated with BTEX

(45) Seaside High School, Seaside, CA

STATUS: Full-scale remediation was completed 06/88. Diesel-contaminated soil was remediated and placed as a road base material prior to paving.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Diesel fuel concentrations were reduced below 1,000 mg/kg with multiple applications of fertilizer, moisture, and tilling. Indigenous bacteria effected the reduction in fuel concentrations.

MEDIA AND CONTAMINANTS: Soil contaminated with diesel

(46) Southern Pacific Transportation Company, Roseville, CA

STATUS: Full-scale remediation was completed 01/91. Started 11/90. Incurred cost: \$310K.

TREATMENT SUMMARY: *Ex situ* land treatment.

MEDIA AND CONTAMINANTS: Soil contaminated with hydrocarbons

(47) Naval Air Station--Fallon, Fallon, NV

STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies have been underway since 09/93. Expected completion 09/95. Pilot-scale studies have been underway since 01/93. Expected completion 06/96. Incurred costs: capital, \$250K; O&M, \$500K. Total expected costs: capital, \$250K; O&M, \$250K. Site has had problems obtaining a water discharge permit from the State of Nevada to discharge treated ground water to the NAS Fallon sewer system due to presence of natural arsenic in ground water. Excessive free fuel in contaminated zones appears to be impeding biodegradation. Once excess fuel is removed, biodegradation rates are expected to increase.

TREATMENT SUMMARY: *In situ* treatment, bioslurping. Oxygen source. Aerobic conditions, indigenous organisms. Nonbiological technologies: vacuum extraction, vacuum enhanced free fuel recovery (provided by vacuum extraction bioventing techniques). Vacuum is pulled in dewatering wells (spaced on 30 ft by 30 ft grid and drilled to 13 ft depths) to promote the rapid aeration of subsurface vadose zone soils by movement of air into soil pores. Since the vacuum (slurper) tubes are situated at the free fuel-ground water interface (9-10 feet depth), free fuel is removed (vacuum assisted) while simultaneously promoting aerobic biodegradation of fuel in the vadose zone through bioventing. This technique is now termed "bioslurping."

MEDIA AND CONTAMINANTS: Vadose soil and saturated soil contaminated with benzene, ethylbenzene, toluene, xylene. Vadose and saturated soil contaminated with JP-5 jet fuel. Ground water contaminated with JP-5 jet fuel, ethylbenzene, 1-methylnaphthalene, benzene, n-butylbenzene, naphthalene, p-xylene, toluene. Arsenic is also present.

(48) East 15th Street Service Station, Anchorage, AK, leaking underground storage tank.

STATUS: Full-scale remediation has been underway since 06/92. Pilot-scale studies have been underway since 02/94. Expected completion 12/94. Incurred cost: \$75K. Total expected cost: \$200K. Winter weather has been an obstacle to bioremediation.

TREATMENT SUMMARY *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms. Nonbiological technologies: vacuum extraction. Treatment involves *in situ* bioventing with monitoring of moisture, carbon dioxide, and nitrates.

MEDIA AND CONTAMINANTS: Soil contaminated with diesel

(49) Texas Tower, Fort Greely, AK, leaking underground diesel fuel storage tank

STATUS: Predesign.

TREATMENT SUMMARY: *In situ* treatment, air sparging. Oxygen source. Aerobic conditions, indigenous organisms. Nonbiological technologies: vacuum extraction. Air sparging and vapor extraction are used jointly to treat contaminated soil and a perched aquifer. Sparging introduces oxygen into the water table, and vapor extraction is used to remove the contaminants.

MEDIA AND CONTAMINANTS: Vadose soil and water contaminated with diesel.

(50) Fairchild Air Force Base, Spokane, WA, contaminated sites consist of either fuel storage facilities or flight-line activity areas

PROCESS 1 STATUS: Full-scale remediation is planned. Currently in predesign. Pilot-scale Studies have been underway since 03/94. Expected completion 03/95. Total expected costs: capital, $50K; O&M, $2,000.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Oxygen source. Aerobic conditions, indigenous organisms. The process consists of a pilot-scale blower with one vent well and three vapor-monitoring points each having sensors at two levels below ground surface. If bioventing is unsuccessful, disposal areas will be capped and soil will undergo active vapor extraction. Ground water will undergo pump and treat with air stripping and GAC. Offsite supply wells and onsite aquifers will be monitored. A throttling blower is used to minimize emissions and allow biodegradation to occur.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with BTEX, TPHs

PROCESS 2 STATUS: Full-scale remediation is planned. Currently in predesign. Pilot-scale studies have been underway since 03/94. Expected completion 03/95. Total expected costs: capital, $50K; O&M, $2,000.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Oxygen source. Aerobic conditions, indigenous organisms. The process consists of a pilot-scale blower with one vent well and three vapor-monitoring points each having sensors at two levels below ground surface. A throttling blower is used to minimize emissions and allow biodegradation to occur.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with BTEX, TPHs.

PROCESS 3 STATUS: Full-scale bioremediation is not planned. Pilot-scale studies have been underway since 03/94. Expected completion 03/95. Total expected costs: capital, $50K; O&M, $2,000. Pilot-scale studies will be sufficient to remediate the contaminated area.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Oxygen source. Aerobic conditions, indigenous organisms. The current studies involve the use of a pilot-scale blower with one vent well and three vapor monitoring points each having sensors at two levels below ground surface.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with BTEX, TPH.

PROCESS 4 STATUS: Full-scale remediation is planned. Currently in predesign. Pilot-scale studies have been underway since 03/94. Expected completion 03/95. Total expected costs: capital, $20K; O&M, $2,000.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Oxygen source. Aerobic conditions, indigenous organisms. A pilot-scale blower is used with one vent well and three vapor-monitoring points each having sensors at two levels below ground surface. A throttling blower is used to minimize emissions and allow biodegradation to occur.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with benzene, TPHs

PROCESS 5 STATUS: Full-scale bioremediation is not planned. Pilot-scale studies have been underway since 03/94. Expected completion 03/95. Total expected costs: capital, $20K; O&M, $2,000. Pilot-scale studies will be sufficient to remediate the site.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Oxygen source. Aerobic conditions, indigenous organisms. The process involves using a pilot-scale blower with one vent well and three vapor-monitoring points each having sensors at two levels below ground surface. A throttling blower is used to minimize emissions and allow biodegradation to occur.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with BTEX, TPHs

PROCESS 6 STATUS: Full-scale remediation is planned. Currently in predesign. Pilot-scale studies have been underway since 07/94. Expected completion 06/95. Total expected costs: capital, $50K; O&M, $5,000.

TREATMENT SUMMARY: *In situ* treatment, air sparging, bioventing. Oxygen source. Aerobic conditions, indigenous organisms. The treatment train involves bioventing for the vadose zone with vapor monitoring points. Air sparging occurs in a downgradient location to volatilize the benzene from the ground water into the vadose zone.

MEDIA AND CONTAMINANTS: Vadose soil contaminted with benzene

ENERGETICS

(1) Hercules Incorporated, Hercules, CA, formerly used for manufacturing explosives

STATUS: Full-scale bioremediation is not planned. Pilot-scale studies were completed 01/91. Started 01/89. The pilot-scale studies were very promising, and cleanup levels were achieved fairly quickly. However, the timing for full-scale bioremediation was not favorable. There were other technical problems. Only landfarming was tried, no slurry type bioremediation.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Solid-phase bioremediation was undertaken at the pilot scale with 1 cubic yard boxes of soil.

MEDIA AND CONTAMINANTS: Soil contaminated with explosives (DNT, nitrobenzene, TNT)

PAHs

(1) Charlestown Navy Yard, Boston, MA, harbor

STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies were completed 09/93. Both 30-day and 60-day laboratory scale studies were conducted. They were able to reduce concentrations which varied from 6,000–20,000 ppm according to location, to between 100–300 ppm. The State was looking for target levels of 25 ppm. It was not felt that these could be achieved through bioremediation.

TREATMENT SUMMARY: *In situ* treatment, *in situ* sediment bioremediation. Oxygen source, nutrient addition. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Sediment (creosote, PAHs), Wood preserving wastes

(2) Iron Horse Park, Operable Unit 1 (B&M Lagoon), Billerica, MA

STATUS: Full-scale remediation has been underway since 05/92. Laboratory-scale studies were completed 01/88. Pilot-scale studies were completed 09/93. Total expected cost: $2M.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Soils and sludges are excavated to treatment cell. Nutrients, moisture, and aeration conditions are optimized for indigenous organisms. Contaminated material is applied in 6- to 9-in. lifts.

MEDIA AND CONTAMINANTS: Sludge and vadose soil contaminated with PAHs, TPHs

(3) Niagara Mohawk Power Corporation, Saratoga Springs, NY

STATUS: Laboratory-scale studies were completed 05/92. Started 02/92. Laboratory-scale feasibility study report currently is being prepared. Depending on results, pilot- and full-scale activity may be undertaken. *In situ* treatment with nutrient addition would be used for soils, and a fluidized bed bioreactor would be used for ground water.

TREATMENT SUMMARY: *Ex situ* treatment, slurry reactor. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Soil contaminated with petroleum (PAHs)

(4) L.A. Clarke & Son, Fredericksburg, VA, former wood preserving site

STATUS: Full-scale remediation is planned. Currently in design. Pilot-scale studies have been underway since 07/92. Total expected cost: $23M. Consent decree includes a provision allowing responsible party to petition EPA to revise cleanup levels. The petition is not yet completed. Therefore, cleanup goals are not yet defined, and it is not known whether bioremediation would be capable of meeting those goals. Although landfarming is still an option, other cleanup technologies are being considered.

TREATMENT SUMMARY: *In situ* treatment, creosote recovery, landfarming. Anaerobic conditions. Nonbiological technologies: *in situ* soil flushing.

MEDIA AND CONTAMINANTS: Sediments and soil contaminated with creosote

(5) Langdale Facility, Sweetwater, TN

STATUS: Full-scale remediation was completed 01/89.

TREATMENT SUMMARY: *Ex situ* land treatment, nutrient addition, and cometabolite. Exogenous organisms. The solid-phase bioremediation land treatment used bacteria, nutrients, and cometabolite.

MEDIA AND CONTAMINANTS: Sludge and soil contaminated with creosote

(6) Reilly Tar & Chemical Company, St. Louis Park, MN, inactive coal tar distillation facility

STATUS: Full-scale remediation is planned. Pilot-scale studies have been underway since 11/92. Expected completion 11/95. Incurred cost: $25K. Total expected cost: $70K.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Nutrient addition. Aerobic conditions, indigenous organisms. A pilot-scale treatability test is being conducted on a 50 square foot area. The technology being tested is bioventing of soils.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with 2-fluorobiphenyl, acenaphthylene, acenaphthene, anthracene, benzo(a)anthracene, benzo(b)fluoranthene, BAP, benzo(k)-fluoranthene, benzo(g,h,i)perylene, chrysene, dibenzo(a,h)anthracene, fluoranthene, fluorene, indeno(1,2,3-cd)pyrene, naphthalene, PAHs, phenanthrene, pyrene.

(7) St. Louis River Interlake/Duluth Tar Site, Duluth, MN, site of coking and tar refining operations (1904–61)

STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies are being conducted. Total expected costs: capital, $88.8K; O&M, $172K. Remedy for PAH-contaminated soils has not been selected. The final RI reports for the soils operable unit currently is being reviewed along with Alternatives Screening Projects.

TREATMENT SUMMARY: *In situ* treatment, bioventing, *in situ* soil bioremediation (*in situ* land treatment). *Ex situ* land treatment. Nutrient addition (nutrients undetermined at this point). Aerobic conditions, indigenous organisms. Nonbiological technologies: thermal desorption, "pure tar" found in isolated "tar seeps" at the site will be thermally destroyed as fuel. Details not yet determined.

MEDIA AND CONTAMINANTS: Soil contaminated with PAHs. Occasional low-level cyanide.

(8) Moss-American, Milwaukee, WI, former creosote site

STATUS: Full-scale remediation is planned. Laboratory-scale studies have been completed. Pilot-scale studies are planned. Percent of clay in soil/sediment may reduce the efficiency of the system. Surfactants used in working process may interfere with bioslurry system. Also, laboratory-scale studies produced erratic results. The bioslurry technique was shown to remove 80–90% of two-, three-, and four-ring PAHs but only 50–60% of five-ring PAHs. The differing degrees of degradation have suggested a review of the bioslurry method. Further studies and additional research are being conducted to determine what method would be most effective in remediating the site. Since the bioslurry technique was unable to remediate test samples to the targeted clean-up level of 6.1 ppm, a higher performance goal of 40–60 ppm has been proposed and may be established. The additional research on the site began summer 1994 and should be complete by fall 1994.

TREATMENT SUMMARY: *Ex situ* treatment, slurry reactor. Nutrient addition (phosphorus, nitrogen), batch flow. Aerobic conditions, indigenous organisms. Nonbiological technologies: soil washing. Soils and sediments will be subjected to soil washing process. The fines and slurry then will be treated in a slurry reactor.

MEDIA AND CONTAMINANTS: Sediments and soil contaminated with creosote

(9) Hudson Refining Company, Cushing, OK, refinery

STATUS: Full-scale remediation has been underway since 01/86. Incurred cost: $1M. Since the refinery has gone into bankruptcy, the state and continuance of bioremediation is uncertain.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Nutrient addition. Aerobic conditions, indigenous organisms. Nonbiological technologies: excavation of soils exhibiting oil and grease concentrations greater than 20,000 ppm. Solid-phase bioremediation of 40 percent of site is being conducted in three phases: (1) active, which consists of aeration and mixing by tilling to a depth of 12 in. or the maximum practicable based on limitations due to soil depth or access to a given biotreatment area; incorporation of soil conditioners to maintain soil pH between 6 and 7.5; maintenance of soil moisture content just below field capacity; and an annual application of fertilizer at an optimal rate estimated to be 300 to 500 pounds per acre; (2) enhanced, which is consistent with the active biotreatment except that soil tilling may be eliminated; and (3) augmented, which is

consistent with the enhanced biotreatment program except that treatment ceases when performance standards are met.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with BAP, benzo(a)anthracene, chrysene, total oil and grease, total PAHs

(10) Scott Lumber, Alton, MO, abandonded wood treating facility

STATUS: Full-scale remediation was completed 11/91. Started 06/90. Incurred costs: capital, $700K; O&M, $500K. Total expected cost: O&M, $600K. Cost per year: O&M, $300K. Health-based risk levels for PAHs were changing and inconsistent.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Conventional land treatment with a 7-acre, closed system, and water recirculation.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with acenaphthylene, fluorene, anthracene, benzo(b)fluoranthene, benzo(a)anthracene, BAP, benzo(g,h,i)perylene, benzo(k)fluoranthene, chrysene, dibenzo(a,h)anthracene, fluoranthene, indeno(1,2,3-cd)pyrene, naphthalene, PAHs, phenanthrene, pyrene

(11) Burlington Northern Tie Plant, Somers, MT, former railroad tie treatment plant

STATUS: Full-scale remediation has been underway since 09/93. Laboratory-scale studies have been completed. Total expected cost: $11M. Pilot-scale field activities have been initiated because of low soil transmissivities. Onsite pumping tests were completed in the third quarter of FY1991. A portion of the site is adjacent to a large lake.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation, *in situ* soil bioremediation (*in situ* land treatment). *Ex situ* land treatment. Oxygen source, nutrient addition (nitrogen, phosphorus). Aerobic conditions, indigenous organisms. Nonbiological technologies: surface treatment of extracted ground water by carbon adsorption. A 14-acre land treatment unit was constructed on site for excavated soils (about 60,000 cubic yards). Ground water and soil below the water table will be treated *in situ* by injection/withdrawal wells. Nutrients and oxygen will be added (about 70,000 cubic yards).

MEDIA AND CONTAMINANTS: Soil and ground water contaminated with PAHs. Zinc is also present.

(12) Utah Power and Light, Idaho Falls, ID, wood pole treatment yard

STATUS: Full-scale bioremediation is not planned. Pilot-scale studies were completed 07/91. Addition of water or mixing and drying were not monitored. There were no indications of dilution or volatilization. Tests were determined to be unsuccessful.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Aerobic conditions, exogenous organisms. Nonbiological technologies: pump and treat. This pilot-scale study monitored oxygen and pH in different nutrient and media combinations.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with PAHs.

HALOGENATED HYDROCARBONS

(1) General Electric, Pittsfield, MA

STATUS: Full-scale bioremediation is not planned. Laboratory-scale and pilot-scale studies are being conducted. Bioremediation of PCBs is too slow or nonexistent.

TREATMENT SUMMARY: *Ex situ* treatment, sequencing batch reactor, batch flow. Anaerobic conditions, indigenous organisms. Nonbiological technologies: incineration, flotation separation.

MEDIA AND CONTAMINANTS: Sediments contaminated with PCBs

(2) General Electric--Woods Pond, Pittsfield, MA

STATUS: Full-scale bioremediation is not planned. Laboratory-scale and pilot-scale studies are being conducted. At present there is no known way to speed up bioremediation of PCBs to a rate that would make technology commercially viable as an option for site cleanup.

TREATMENT SUMMARY: *In situ* treatment, confined treatment facility for sediments. Nutrient addition, anaerobic conditions, indigenous organisms. Nonbiological technologies: incineration, flotation separation.

MEDIA AND CONTAMINANTS: Sediments contaminated with PCBs

(3) General Motors--Central Foundry Division, Massena, manufacturing site

STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies were completed 12/93. Started 04/93. Three techniques were tested: bioremediation, solvent extraction, and thermal desorption. Final results are not yet complete, but it appears that the recommendation will be that thermal desorption be employed. Bioremediation was not able to get the contaminant concentrations down to acceptable levels, no further than around 100 ppm.

TREATMENT SUMMARY: *Ex situ* treatment, slurry reactor, batch flow. Aerobic conditions, indigenous organisms. Nonbiological technologies: chemical extraction, chemical treatment, thermal desorption.

MEDIA AND CONTAMINANTS: Sediments, sludge and soil contaminated with PCBs

(4) Drake Chemical, Lock Haven, PA

STATUS: Full-scale remediation is planned. Currently in predesign.

TREATMENT SUMMARY: Aerobic conditions.

MEDIA AND CONTAMINANTS: Soil and ground water contaminated with DCE, fenac, pesticides

(5) Texas Eastern Gas Pipeline, Armaugh, PA

STATUS: Full-scale remediation is planned. Laboratory-scale and pilot-scale studies are being conducted.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). *Ex situ* treatment, sequencing batch reactor. Nutrient addition, batch flow. Aerobic conditions, exogenous organisms. Nonbiological technologies: solid-phase extraction process (physical separation). There are two bioreactor processes: one biological process and one soild-phase extraction process. Using a proprietary process, PCB contaminant is extracted from soil onto a solid material of significantly reduced volume. Solid material with PCBs is then incinerated.

MEDIA AND CONTAMINANTS: Soil contaminated with PCBs. The presence and effect of other contaminants on the bioremediaton process has not been investigated

(6) ARC, Gainesville, VA

STATUS: Full-scale remediation was completed 06/91. Started 10/89.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, exogenous organisms.

MEDIA AND CONTAMINANTS: Soil contaminated with solvents (chlorobenzene)

(7) Orkin Facility, Fort Pierce, FL, pest control and termite control branch facility

STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies have been underway since 03/93. Expected completion 10/94. Pilot-scale studies are planned.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Oxygen source, nutrient addition. Aerobic conditions, exogenous organisms. Nonbiological technologies: chemical treatment. Fungi strains, nutrients, and soil will be mixed and then incubated under oxygenated conditions.

MEDIA AND CONTAMINANTS: Soil contaminated with pesticides (chlordane, heptachlor)

(8) Fisher-Calo, LaPorte, IN

STATUS: Predesign. There is only a remote possibility that bioremediation will be used to remediate entire site.

TREATMENT SUMMARY: Bioremediation treatment not yet established.

MEDIA AND CONTAMINANTS: Soil contaminated with PCBs. Ground water contaminated with DCE, DCA, TCE.

(9) Seymour Recycling, Seymour, IN, solvent recycling site

STATUS: Full-scale remediation was completed 09/90. Incurred costs: capital, $900K; O&M, $100K. Since a multi-layer cap was applied over the bio-applied soil, there is no way to sample the contaminated soil. The RI in 1984 found more than 54 organic chemicals. It was difficult to landfarm nutrients below the surface as far as we would have preferred.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation, *in situ* soil bioremediation (*in situ* land treatment). Nutrient addition (potassium, nitrogen, phosphorous, sulfur). Aerobic conditions, indigenous organisms. Nonbiological technologies: vacuum extraction, multi-layer cap. The nutrients were landfarmed on the source area prior to construction and operation of the vacuum extraction system and the multi-layer cap. Bioremediation is just one aspect of our remediation. Contaminants do migrate from the source area to a ground water plume. It is hoped that the landfarming in combination with the vacuum extraction will minimize the contaminant flow to ground water.

MEDIA AND CONTAMINANTS: Soil contaminated with DCE, TCE, vinyl chloride. Ground water contaminated with TCE, benzene, chloroethane, DCE, vinyl chloride

(10) Bendix Corporation/Allied Automotive Site, St. Joseph, MI, active automotive brake manufacturing facility

PROCESS 1 STATUS: Full-scale remediation is planned. Currently being installed. Expected start 09/94. Laboratory-scale studies have been completed. Pilot-scale studies are planned.

TREATMENT SUMMARY: *Ex situ* treatment, fixed film, plug flow. Aerobic conditions, indigenous organisms. Nonbiological technologies: vacuum extraction. Vacuum extraction of the vadose zone will feed into a bioreactor.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with DCA, TCE

PROCESS 2 STATUS: Full-scale remediation is planned. Laboratory-scale studies are being conducted. Recent sampling found elevated levels of ethene in the aquifer, implying an extensive degree of intrinsic mineralization. This unassisted, intrinsic process of biodegradation may be adequate to remediate the ground water.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. Aerobic and anaerobic conditions, indigenous organisms. At this point, no treatment process is foreseen. Intrinsic degradation may be adequate for remediation.

MEDIA AND CONTAMINANTS: Ground water contaminated with DCE, DCA, TCE, vinyl chloride

(11) Burlington Northern, Brainerd, MN

STATUS: Full-scale remediation is being conducted. Pilot-scale studies were completed 01/86.

TREATMENT SUMMARY: *Ex situ* land treatment, nutrient addition. Aerobic conditions, indigenous organisms. Nonbiological technologies: thermal desorption and pump and treat for ground water. Activities include waste application to treatment area, start up, cultivation, irrigation, soil sampling, water sampling, meteorological monitoring, and nutrient applications.

MEDIA AND CONTAMINANTS: Vadose soil and ground water contaminated with PCP

(12) Sheboygan River and Harbor, Sheboygan, WI, contaminated sediments in river and harbor

PROCESS 1 STATUS: Full-scale bioremediation is not planned. Laboratory-scale and pilot-scale studies have been completed. Delays in pilot-scale study due to additional laboratory-scale tests and coordination with ARCS Program as Pilot Demonstration Project for Sheboygan AOC. Effectiveness and reliability are unproven. Process takes a long time. TSCA requirements: might not be able to achieve a 2 ppm treatment level.

TREATMENT SUMMARY: *Ex situ* treatment, confined treatment facility (tank). Aerobic and anaerobic conditions, indigenous organisms. Nonbiological technologies: armoring (capping) pilot-scale study was undertaken on armoring effects on biodegradation, solidification/stabilization, thermal extraction, chemical dechlorination, solvent extraction. The confined treatment facility is a 4-sided tank (106 × 135 × 10 ft high) divided into four cells: two for control, two for study. The eastern wall has two long narrow cells for passive flow-through treatment of water before discharge. Both aerobic and anaerobic conditions in the sediments are being investigated, with possible pulsing back and forth.

MEDIA AND CONTAMINANTS: Sediments contaminated with PCBs

PROCESS 2 STATUS: Predesign. Several rounds of samples have been collected but results are inconclusive.

TREATMENT SUMMARY: *In situ* treatment, *in situ* sediment bioremediation. Capped sediments in the river provide an *in situ* biodegradation study for natural degradation to examine the trend in dechlorination.

MEDIA AND CONTAMINANTS: Sediments contaminated with PCBs

(13) Dow Chemical Company--Louisiana Division, Plaquemine, LA, leaking above ground storage tank

STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies were completed 12/90. Pilot-scale studies were completed 12/92. Incurred costs: capital, $250K; O&M, $10K. Total expected cost: $260K. Permeability of the contaminated zones is low, and the supply (injection) of nutrients is difficult. All bioactivity may occur at the well screen, thereby plugging the screen. Unable to move nutrients through the contaminated zones even after hydraulic fracturing.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. Nutrient addition (acetate, glucose, or ethanol proposed). Anaerobic conditions, indigenous organisms. Nonbiological technologies: pump and treat. Nutrients are pulsed into the ground. EDC and the nutrient are the substrates or the food source and ethylene, methane, and chloride are the products of the reaction. The methane and ethylene are expected to be in gaseous form and dissipate through the upper soils.

MEDIA AND CONTAMINANTS: Ground water contaminated with 1,1,1-TCA, 1,1-DCA, 1,1-DCE, 1,2-DCA, chloroethane

(14) Texas Eastern Gas Pipeline, Saint Francisville, LA, site contaminated by natural gas pipeline operations

STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies have been completed. Pilot-scale studies were completed 04/93. This was a treatability study carried out by a contractor hired by Texas Eastern. The studies indicated that bioremediation failed to reduce PCB contamination to within the necessary levels.

Bioremediation of PCBs was not demonstrated in the 2-year duration of the experiment. Although bioremediation was considered, it was rejected and the site was landfilled.

TREATMENT SUMMARY: *Ex situ* treatment, biotreatment of soil in a plastic liner. Aerobic conditions, exogenous and indigenous organisms. There are two bioreactor processes—one biological process and one solid-phase extraction process (each treating the material as a liquid and solid, respectively). Using a proprietary process, PCB contaminant is extracted from soil on to a solid material of significantly reduced volume. Solid material with PCBs is then incinerated.

MEDIA AND CONTAMINANTS: Soil contaminated with PCBs

(15) Lake County Weed Control, pesticide storage and truck filling facility

STATUS: Full-scale bioremediation is not planned. No longer being considered due to natural degradation of pesticide levels to levels too low to perform pilot-scale study on and due to failure of related studies to substantially reduce pesticide levels.

TREATMENT SUMMARY: Aerobic and anaerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with 2,4-D, atrazine, 4,4'-DDD, 4,4'-DDE, 4,4'-DDT, aldrin, á-BHC, â-BHC, chlordane, dicamba, dieldrin, endrin, Far-go, methoxychlor, Tordon

(16) Middle Mountain Silvex, Greenlee County, AZ, 1971 herbicide dump in a National Forest

STATUS: Full-scale remediation was completed 09/92. Incurred cost: $19.5K.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Nonbiological technologies: photodegradation by ultraviolet sunlight at elevation of 9,000 ft above sea level. Excavated soil was placed on a prepared bed (dirt road). Nutrients and water were added. Rototilling was done periodically. The bed was prepared to optimize photodegradation using high altitude (9,000 ft ASL) UV sunlight. Road was lined with earthen berms 12 to 24 in. high and graded to eliminate rain water runon and runoff.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with herbicides (2,4,5-T, 2,4-D)

(17) Harmon Field, Tulare County, CA, former crop duster facility contaminated with pesticides

PROCESS 1 STATUS: Full-scale remediation is planned. Pilot-scale studies are planned. Expected completion 12/94. Total expected cost: capital, $50K. The project is still in its planning stages: proposed testing the effect of plant root activity on bioremediation; to test the activity, proposed growing rice, which requires that water be recirculated continuously, creating technical problems regarding the handling of water.

TREATMENT SUMMARY: *Ex situ* treatment, lined cells on aboveground containers, organic material and lime addition. Aerobic conditions, indigenous organisms. Nonbiological technologies: thermal desorption. Thermal desorption has been proposed as a means of remediating the soil; however, it is not the only technology being considered. Rice might also be grown in some of the plots to assess the effect of plant roots on bioremediation.

Lined cells and/or aboveground containers might be used for containment during testing.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with pesticides (DDT, toxaphene)

PROCESS 2 STATUS: Full-scale bioremediation is not planned. Pilot-scale studies were completed 11/90. Started 05/90. Incurred cost: capital, $120K. Total expected cost: capital, $120K.

Tests were conducted on thirteen 5-gallon buckets of soil. Results showed that pesticides were not removed from the containers after 192 days of treatment. Due to the high variability of the data, however, it is unclear whether some degradation occurred. A larger scale study may be conducted to achieve statistically significant results. Results of this testing were inconclusive regarding the effectiveness of the bioremediation process in remediating the site.

TREATMENT SUMMARY: *Ex situ* land treatment, lime and moisture addition. Aerobic and anaerobic conditions, exogenous and indigenous organisms. Nonbiological technologies: thermal desorption. Soils that were tested were obtained from two different areas at the site. One area from which samples were obtained indicated relatively low concentrations of organochlorine pesticides while the other area from which samples were obtained contained high concentrations of the pesticides.

MEDIA AND CONTAMINANTS: Soil contaminated with pesticides (à-BHC, chlordane, dicofol, 4,4'-DDE, 4,4'-DDD, 4,4'-DDT, endosulfan II, endrin, endrin aldehyde, heptachlor, heptachlor-epoxide, methoxychlor, toxaphene)

INORGANIC

(1) Coakley Landfill, North Hampton, NH

STATUS: Full-scale remediation is planned. Currently in predesign. Expected start 01/96.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. Nonbiological technologies: metal precipitation and air stripping. Biological treatment forms only a small portion of overall treatment.

MEDIA AND CONTAMINANTS: Ground water contaminated with ammonia

METALS

(1) Allied Chrome Works, Baltimore, MD, chromium ore processing plant

PROCESS 1 STATUS: Full-scale bioremediation is not planned. Pilot-scale studies were completed 01/92. Incurred cost: $200K. Pilot-scale studies in the field indicated that the site geology was too problematic for full-scale investigation and treatment. There were problems with preferential flows. A cap treatment was chosen for full-scale remediation.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. Nutrient addition (mineral salts and molasses). A fermentation broth was made *ex situ* with seed cultures of sulfate-reducing bacteria, mineral salts, and molasses. This broth was injected into the ground water. This process transformed soluble, toxic CR(VI) into insoluble, nontoxic Cr(III).

MEDIA AND CONTAMINANTS: Sediments, soil, and ground water contaminated with hexavalent chromium

PROCESS 2 STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies were completed 01/91. Started 01/90. Incurred cost: $200K. Personnel, cost, and time factored into the decision not to continue *ex situ* treatment in pilot-scale study, even though the lab-scale treatment had given good results.

TREATMENT SUMMARY: *Ex situ* treatment, septic tank reactor, completely mixed flow. Anaerobic conditions, indigenous organisms. Contaminated materials were placed in a septic tank under anaerobic conditions with fermented molasses and sulfate reducing bacteria (SRB). This process transformed soluble, toxic Cr(VI) into insoluble, nontoxic Cr(III).

MEDIA AND CONTAMINANTS: Sediments, soil, and ground water contaminated with hexavalent chromium

MIXED

(1) Baird and McGuire, Holbrook, MA

STATUS: Full-scale remediation has been underway since 01/93. Incurred cost: capital, $13M. Cost per year: O&M, $2M.

TREATMENT SUMMARY: *Ex situ* treatment, activated sludge, completely mixed flow. Aerobic conditions, exogenous organisms. Nonbiological technologies: chemical treatment for ground water and incineration for soil.

MEDIA AND CONTAMINANTS: Ground water contaminated with wood preserving wastes, pesticides, solvents. (BTEX, chlordane, creosote)

(2) Sylvester, Nashua

PROCESS 1 STATUS: Predesign. There have been problems providing enough nutrients to maintain an active biomass.

TREATMENT SUMMARY: *Ex situ* treatment, extended aeration.

MEDIA AND CONTAMINANTS: Ground water contaminated with solvents (benzene, chloroform, MEK, 1,1,2-TCA, chlorobenzene, 1,1-DCA, 1,1,1-TCA, methylene chloride, methylmethacrylate, PCE, phenols, TCE, toluene, trans-1,2-DCA, vinyl chloride)

PROCESS 2 STATUS: Full-scale remediation has been underway since 01/86. Pilot-scale studies were completed 01/83. There have been problems providing enough nutrients to maintain an active biomass. An evaluation process is underway, which will conclude at the end of 1994. After this evaluation a decision will be made concerning the next step.

TREATMENT SUMMARY: *Ex situ* treatment, activated sludge. This is an activated sludge reactor using extended aeration.

MEDIA AND CONTAMINANTS: Ground water contaminated with benzene, chloroform, MEK, 1,1,2-TCA, chlorobenzene, 1,1-DCA, 1,1,1-TCA, methylene chloride, methylmethacrylate, PCE, phenols, TCE, toluene, trans-1,2-DCA, vinyl chloride.

(3) Whitmoyer Labs, Myerstown, PA, vetrinary food additives and treatment facility

STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale and pilot-scale studies are planned. Bioremediation will only be used on a very small portion of the site, since the main contaminant is arsenic. There is one area that is high in organics, but bioremediation is still a couple of years away.

TREATMENT SUMMARY: *Ex situ* treatment, biological treatment. Nonbiological technologies: chemical treatment, fixation, incineration, containment, pump and treat.

MEDIA AND CONTAMINANTS: Vadose and saturated soils contaminated with benzene, aniline, PCE, and TCE

(4) Atlantic Wood, Portsmouth, VA , inactive wood preserving site

STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale and pilot-scale studies are planned. Feasibility study results currently are being reviewed. Type of treatment will not be determined until review is completed. The presence of dioxins and furans and metals might be a problem.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions. Nonbiological technologies: *in situ* soil flushing, soil washing, thermal desorption, incineration.

MEDIA AND CONTAMINANTS: Sediments and soil contaminated with wood preserving wastes (PAHs, PCP). Dioxins, furans, arsenic, zinc, and copper are also present.

(5) Avtex Fibers, Front Royal, VA, inactive chemical processing plant

STATUS: Full-scale remediation is being conducted.

TREATMENT SUMMARY: *Ex situ* treatment, activated sludge, completely mixed flow. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Ground water contaminted with organic compounds (carbon disulfide). Arsenic, zinc, lead, cadmium, carbon disulfide, and hydrosulfide are also present.

(6) Ordnance Works Disposal Area, Morgantown, WV, former ammonia production site

STATUS: Full-scale remediation is planned. Laboratory-scale studies have been underway since 02/93. Expected completion 12/94. Pilot-scale studies are planned. Total expected cost: $8.3M. There may be problems at this site associated with: (1) achieving the cleanup levels, (2) extrapolating data from the treatability studies, and (3) determining usable amendments for the treatability studies. In addition, we are having difficulty with the heterogeneity of the soil. The process is still in the laboratory-scale phase. The pilot-scale phase has not yet been started, and there is no estimate when it will start. There have been many delays. There is no immediate threat to the study. As long as the study is being funded and there are no unsuccessful results, it can be continued.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Nonbiological technologies: solidification of inorganics.

MEDIA AND CONTAMINANTS: Soil contaminated with PAHs. Arsenic, cadmium, copper, lead are also present.

(7) Alabama State Docks, Mobile, AL, inactive wood preserving site

PROCESS 1 STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies have been completed. Pilot-scale studies are being conducted. Problems have arisen over regulatory concerns when managing treated material.

TREATMENT SUMMARY: *Ex situ* treatment, fluidized bed, completely mixed flow. Aerobic conditions, exogenous organisms. Nonbiological technologies: granular activated carbon. The first step in the process is chemical oxidation with potassium permanganate to remove iron followed by coagulation/flocculation using polymers and gravity settling. An aerobic attached growth process follows this and, if necessary, GAC removal may be used.

MEDIA AND CONTAMINANTS: Ground water contaminated with PAHs, benzene, PCP. Lead is also present.

PROCESS 2 STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies have been completed. Pilot-scale studies are planned.

TREATMENT SUMMARY: *Ex situ* land treatment.

MEDIA AND CONTAMINANTS: Soil contaminated with PAHs, PCP

(8) Stallworth Timber, Beatrice, AL, active wood preserving site, contamination in former swampland filled with wood chips

STATUS: Full-scale remediation is planned. Currently in predesign.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). *Ex situ* treatment, activated sludge, completely mixed flow. Aerobic conditions, exogenous and indigenous organisms. Nonbiological technologies: chemical treatment, clarification, ultraviolet oxidation. Ground water is pumped through a clarifier and an oil/water separator. It then undergoes biological and chemical treatment, hydrogen peroxide addition and UV oxidation, and granular activated carbon treatment. Soil is treated by applying the treated ground water and nutrients.

MEDIA AND CONTAMINANTS: Soil and ground water contaminated with creosote, PCP

(9) American Creosote Works--Pensacola, Pensacola, FL, inactive wood preserving site

PROCESS 1 STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies were completed 11/91. Total expected cost: $5M. Bioremediation was not effective for remediation of

dioxins in soils, and it was only effective in degrading PCPs and carcinogenic PAHs at a rate of 30%.

TREATMENT SUMMARY: *Ex situ* treatment, sequencing batch reactor, slurry reactor, batch flow. Aerobic conditions, indigenous organisms. Nonbiological technologies: soil washing. Soil washing was a pre-treatment step for the reactors. It was used to help with the degradation of contaminants but proved ineffective.

MEDIA AND CONTAMINANTS: Soil contaminated with PAHs, PCP

PROCESS 2 STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies are planned. Expected start 01/95. Pilot-scale studies are planned. Expected start 01/96. Total expected costs: capital, $3.9M; total, $5.9M. Costs per year: O&M, $492K. Addition of other enhancing agents during DNAPL recovery may inhibit bioremediation. Injection of any nutrients or hydrogen peroxide may be prohibited by State.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. Hydrogen peroxide, nutrient addition (nutrients not yet determined). Aerobic conditions, indigenous organisms. Nonbiological technologies: soil washing, enhanced DNAPL recovery and separation prior to *in situ* biotreatment of ground water.

MEDIA AND CONTAMINANTS: Ground water contaminated with benzene, acenaphthene, fluoranthene, dibenzofuran, naphthalene, PAHs, PCP. It is possible that zinc and dioxins are also present.

PROCESS 3 STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies were completed 11/91. Total expected cost: $5M. Bioremediation was not effective for remediation of dioxins in soils. Biotreatment was unable to achieve remedial goals for PCPs and carcinogenic PAHs.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Nonbiological technologies: soil washing.

MEDIA AND CONTAMINANTS: Soil contaminated with PAHs, PCP

(10) Cabot Koppers, Gainesville, FL, active wood preserving site

STATUS: Full-scale remediation is planned. Laboratory-scale studies were completed 04/93. Pilot-scale studies are planned. This site is an active facility. The purpose of considering the cleanup was to prevent contamination of the ground water, and it was thought initially that the contamination was only to 6 to 7 feet. Bioremediation was being considered for two source areas under structures, where it was hard to excavate. However, it was suddenly discovered that there was contamination to 25 feet, and that there was a serious DNAPL problem. In addition, the bench-scale bio tests did not show cleanup level achievement. At the present, there is a rethinking of strategy, and work is beginning on the submission of an FS work plan. A pump and treat system for ground water is being set up in order to deal with the DNAPL now, and soil will be dealt with later. A pilot-scale study for the bio is probably the next step.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Hydrogen peroxide, plate counts, respirometry, analytical assays. Aerobic conditions, indigenous organisms. Nonbiological technologies: soil washing, solidification. Treatment was solid-phase bioremediation involving surface treatment cell lined with clay berms 5 to 6 feet deep.

MEDIA AND CONTAMINANTS: Soil contaminated with PAHs, fluorene, naphthalene, PCP, phenol. Arsenic, chromium are also present.

(11) Coleman-Evans, White House, FL, inactive wood preserving site

STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies have been completed. Total expected cost: $8.6M. Dioxins have been identified and were found to obstruct the biodegradation process. The identification of dioxin in the soil increased the contaminated area from 27,000 cubic yards to 52,000 cubic yards. No document of the treatability studies was ever drafted. Bioremediation was ineffective for the removal of dioxins although the process

was effective in degrading PCP in treatability studies. Bioremediation is no longer being considered at the site, and the ROD is being amended. Thermal desorption, capping, or incineration (all in conjunction with ground water pump and treat) are alternatives being considered to address dioxin contamination.

TREATMENT SUMMARY: *Ex situ* treatment, slurry reactor, batch flow. Aerobic conditions, exogenous organisms. Nonbiological technologies: soil washing, solidification/stabilization. Proposed treatment involved (1) soil washing to suspend contaminants in wash water, (2) biotreatment of wash water, (3) solidification/stabilization of biotreatment fines, and (4) dewatering recovery and treatment.

MEDIA AND CONTAMINANTS: Soil contaminated with dioxin, PCP. Arsenic is also present.

(12) Dubose Oil, Cantonment, FL, inactive waste oil recycling facility

STATUS: Full-scale remediation has been underway since 11/93. Laboratory-scale studies were completed 11/88. Started 01/88. Pilot-scale studies are planned. Total expected cost: $3M. Pilot study was delayed due to difficulty in locating soils exceeding cleanup levels. However, full-scale operation proceeded on schedule.

TREATMENT SUMMARY: *Ex situ* treatment, pile. Aerobic conditions, indigenous organisms. Nonbiological technologies: carbon adsorption for treatment of wastewater. Treatment involves windrowing with aeration; soil is taken out of a vault and put in treatment buildings in 4 ft. high piles. Piles are aerated, and nutrients and biological inocula are added. Bioremediation cells are lined with HDPE to prevent migration.

MEDIA AND CONTAMINANTS: Soil contaminated with PCP, benzene, DCE, PNAs, TCE, xylene

(13) Silvex, Saint Augustine, FL

STATUS: Full-scale remediation has been underway since 10/93. Laboratory-scale studies were completed 08/91. Started 01/91. Pilot-scale studies were completed 10/92. Started 01/92. Incurred costs: capital, $560K; O&M, $330K. Total expected costs: capital, $585K; O&M, $400K; total, $910K. The entire 16 gpm system was designed, mobilized, and constructed as part of an IRM project in 9 weeks. The greatest obstacle has been the treatment of vapors/off-gas from the bioreactor and equalization tank, which will react with a vapor GAC system, due to heat liberated from the oxidation of ketones with charcoal. Not yet mobilized is a large-scale biofilter system, by EG&G, which will be constructed by mid-summer, and is "guaranteed to remove the very pungent odors," which include mercaptons, from the ground water.

TREATMENT SUMMARY *Ex situ* treatment, fixed film, completely mixed flow. Aerobic conditions, exogenous organisms. Nonbiological technologies: soil solidification. The biotreatment process is currently a field pilot study system using a BioTrac fixed film reactor. This is similar to the SITE demonstration project recently conducted for the U.S. EPA by BioTrac. See Technology Demonstration Summary "Biological Treatment. Ground Water by BioTrac, Inc." EPA/540/55-91/001.

MEDIA AND CONTAMINANTS: Ground water contaminated with acetone, benzene, 2-butanone, chloroform, 1,1,1-TCA, 2,4-dimethylphenol, cresols, ethylbenzene, methylene chloride, MIBK, toluene. Cadmium, chromium, copper, lead, nickel, silver, zinc are also present.

(14) White House Waste, White House, FL, waste oil recycling sludge pit facility

STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies were completed 09/91. Total expected costs: capital, $15.5M; O&M, $3.4M. Bioremediation is a proposed remedy, presently under public comment. If accepted, an amended ROD will follow. Solidification/stabilization will follow bioremediation in the treatment train due to the presence of lead.

TREATMENT SUMMARY: *Ex situ* treatment, slurry reactor, batch flow. Aerobic conditions, exogenous organisms. Nonbiological technologies: soil washing, solidification/stabilization. Treat-

ment involves (1) soil washing to suspend contaminants in wash water, (2) biotreatment of wash water, (3) solidification/stabilization of biotreatment fines, and (4) ground water recovery and treatment.

MEDIA AND CONTAMINANTS: Soil contaminated with BAP, 1,4-dichlorobenzene, benzene, 2-methylnaphthalene, chlorobenzene, di-n-butyl phthalate, methylene chloride, naphthalene, PCB 1260, PCE, phenol, TCE, toluene. Ground water contaminated with acetone, BAP, benzene, bis(2-ethylhexyl)phthalate, carbon disulfide, 2-methylnaphthalene, di-n-butyl phthalate, ethylbenzene, m-cresol, MEK, naphthalene, p-cresol, phenol, TCE, toluene, xylene. Lead and other inorganics are also present

(15) Shavers Farm, Lafayette, GA

STATUS: Pilot-scale studies have been completed.

TREATMENT SUMMARY: Bioremediation treatment not yet established.

MEDIA AND CONTAMINANTS: Soil contaminated with benzoic acid, benzonitrile, dicamba, dichlorosalicyclic acid

(16) Escambia Wood Preserving Site--Brookhaven, Brookhaven, MS, inactive wood preserving site

STATUS: Full-scale bioremediation is not planned. Pilot-scale studies were completed 11/92. Started 06/92. There is a lack of information on the success of this technology at field scale; however, the field treatability study showed reduction in PCP and creosote—up to 86% for PCP, and 96% for 3-ringed PAH creosote compounds.

TREATMENT SUMMARY: *Ex situ* treatment, white rot fungi treatment. Aerobic conditions, exogenous and indigenous organisms. Application of white rot fungus (P. chrysosporium) to contaminated soils for degradation of pentachlorophenol and PAHs.

MEDIA AND CONTAMINANTS: Soil contaminated with creosote, PCP

(17) Southeastern Wood Preserving, Canton, MS, inactive wood preserving site

STATUS: Full-scale remediation was completed 06/94. Total expected cost: $2.2M. Variability of analytical results using different soil extraction methods was highly significant. Even within each method, there was wide variability in treatment results, possibly from analytical methods or from the less-than-expected homogeneity in the soil slurries.

TREATMENT SUMMARY: *Ex situ* treatment, slurry reactor, batch flow. Aerobic conditions, exogenous and indigenous organisms. Nonbiological technologies: soil washing. Soil is sent through shaker screens then mixed with water and cycloned to remove debris and sand. Slurry mixture is then pumped to reactors, where it is aerated, mixed constantly, and amended with nutrients and a defoaming mixture as necessary. Heat is also added to final batches during cooler weather.

MEDIA AND CONTAMINANTS: Soil contaminated with PAHs. Pentachlorophenol (PCP) is also present.

(18) Cape Fear Wood Preserving, Fayetteville, NC, inactive wood preserving site

STATUS: Full-scale remediation is planned. Currently in design. Laboratory-scale studies were completed 01/90. Pilot-scale studies are planned. Expected start 06/95. Laboratory-scale study was terminated due to time costraints. Biodegradation reduced average total PAH levels and carcinogenic PAH levels from 306 mg/kg and 44 mg/kg, respectively, to 50 mg/L and 14 mg/L in 18 days. Pilot-scale work is needed to confirm effectiveness; overall results suggest longer incubation period could result in further reduction of PAHs to below cleanup goals.

TREATMENT SUMMARY: *Ex situ* treatment, slurry reactor, batch flow. Aerobic conditions, indigenous organisms. Nonbiological technologies: soil washing, solidification. Soil washing is performed with the clean large soil aggregate being returned to the excavated areas, and the

slurry generated by soil washing process fed into bioreactor. Clean soil fines are returned to excavated areas. If metals become a problem with soil fines, then the soil fines will be solidified.

MEDIA AND CONTAMINANTS: Sediments, soil and ground water contaminted with PAHs. Arsenic and chromium are also present.

(19) Celanese Fibers Operations, Shelby, NC, active facility producing polyester polymer chip and filament yarn

STATUS: Full-scale remediation is being conducted. Incurred cost: $1.5M. System has experienced biomass upsets. The cause has not been determined, but measures have been taken to deal with them and have been fairly successful. The ROD did not specify the cleanup levels for chemical specific contaminants. Although the efficiency of the system is monitored based on BOD, COD, and TOC, specific reductions in chemicals of concern have not been analyzed or determined. In the last 5 years, the two-tier extraction well system has averaged 90% removal of TOC and 80% removal of BOC. A total of 460,900 lbs of TOC, 165,000 lbs of COD, and 286,000 lbs of BOD have been removed from the inner-tier well system.

TREATMENT SUMMARY: *Ex situ* treatment, sequencing batch reactor, batch flow. Aerobic conditions, exogenous and indigenous organisms. Nonbiological technologies: chemical treatment, the front-end technologies used to help out the bioremediation are pH adjustment, equalization tank, and a tank separator to take care of iron. Other technologies used after the bioremediation are air stripping and carbon adsorption. Ground water from nine inner-tier extraction wells is first neutralized. After the influent is neutralized and metals are removed in the plate separator, the ground water is fed into the sequencing batch reactor where organics are removed. Ground water then flows through an air stripper tower and a carbon adsorption process to further remove organics. The performance of the system is monitored, measured by reductions in TOC, COD, and BOD.

MEDIA AND CONTAMINANTS: Ground water contaminated with acetone, 1,2-DCE, ethylene glycol. Lead, chromium, PAHs are also present.

(20) Charleston Air Force Base, Charleston, SC, former fire training area and fuel hydrant system

STATUS: Full-scale remediation is planned. Pilot-scale studies were completed 05/94. Started 11/92. Bioventing will be difficult due to high ground water table and seasonal variation of ground water elevation and direction. Studies are being conducted to assess if bioventing should be implemented at this site and also to determine what technologies would be most effective.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Oxygen source. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with 1,1,1-TCA, BTEX jet fuel, PCE, 1,1-DCE, dichloromethane, TCE, trans-1,2-DCE, vinyl chloride. Lead is also present.

(21) Koppers/Florence, Florence, SC, active wood preserving facility

PROCESS 1 STATUS: Full-scale remediation is planned. Currently in predesign. Pilot-scale studies are planned. Expected completion 07/95. There have been many negotiations involved with various parties, including the state, trying to address all the concerns. The main state concern is of the contaminants being forced further into the aquifer. It took a while to get the document to the approval stage. The general lack of experience of others doing *in situ* treatment with these types of waste was also an obstacle.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, exogenous and indigenous organisms. Nonbiological technologies: ground water extraction, pretreatment, and discharge to a POTW. Soil is excavated and placed in 6 ft by 6 ft boxes with roofs, where treatment is carried out.

MEDIA AND CONTAMINANTS: Soil contaminated with PAHs, PCP

PROCESS 2 STATUS: Full-scale remediation is planned. Currently in predesign. Pilot-scale studies are planned. Expected completion 07/95. There have been many negotiations with the various parties involved, including the state, trying to address all concerns. The main concern of the state is of the contaminants being forced further into the aquifer. It took a while to get the document to the approval stage. The general lack of experience of others doing *in situ* treatment with these types of wastes is also an obstacle.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Hydrogen peroxide. Aerobic conditions, exogenous and indigenous organisms. Nonbiological technologies: ground water extraction, pretreatment, and discharge to a POTW. Plots of land are covered to prevent infiltration of water; *in situ* treatment is carried out. There is a concern whether the contaminants will be flushed, and sampling techniques will be used to verify if contaminants are migrating.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with PAHs, PCP

(22) American Creosote Works—Jackson, Jackson, TN, abandonded wood preserving site

PROCESS 1 STATUS: Full-scale remediation is planned. Laboratory-scale and pilot-scale studies are planned. Hydrogeologic investigation is completed. Remedial action is contingent upon receiving a 10% cost share from state. Funds are available for treatability studies only. This unit, Operable Unit #2, is in the pre-ROD stage. Bioremediation has not yet been selected as a remedy, only a potential one.

TREATMENT SUMMARY: *Ex situ* land treatment, pile. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Ground water contaminated with creosote, PCP. Chromium (+3), copper, and silver are also present.

PROCESS 2 STATUS: Full-scale remediation is planned. Laboratory-scale and pilot-scale studies are planned. State may not have 10% cost share for any remedial action to be undertaken. In this Operable Unit #3, remediation has not yet been a selected remedy, only a potential one.

TREATMENT SUMMARY: *Ex situ* treatment, aerated lagoon. Aerobic conditions, indigenous organisms. Operable Unit #3 is defined as dealing with process area soils and "fixed" creosote sludges in a large capped lagoon.

MEDIA AND CONTAMINANTS: Sludge contaminated with creosote. Vadose and saturated soil contaminated with creosote, PAHs, phenols. Chromium (+3), copper, silver are also present.

(23) Galesburg/Koppers, Galesburg, IL, inactive wood preserving site

STATUS: Full-scale remediation is planned. Currently in predesign.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Nutrient addition.

MEDIA AND CONTAMINANTS: Soil contaminated with chlorophenol, PCP, PAHs, phenols, PNAs

(24) Reilly Tar, Indianapolis, IN, aquifer

STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies have been underway since 01/89. Total expected cost: $15M. Site consists of 60 to 80 ft of aquifer with conductivities of 0.01 to 0.001 with interfingering until units are not continuous (clay); 7,000,000 gallons per day are planned to be pumped from lower zone aquifer. The total amount of ground water to be treated has not yet been determined. A record of decision has only been written for the ground water IRM (proposed cost $15M); other portions of the site are still in the feasibility studies stage, and bioremediation is under consideration.

TREATMENT SUMMARY: *Ex situ* treatment, sequencing batch reactor, completely mixed flow. Nonbiological technologies: chemical extraction.

MEDIA AND CONTAMINANTS: Ground water contaminated with benzene, ammonia, pyridine

(25) Cliff/Dow Disposal Site, Marquette, MI, former charcoal producing site, with tar residues

STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies were completed 08/93. Started 12/92. Biotreatment process did not reduce PAHs to below risk-based numbers in a reasonable time frame (22 weeks). Further sampling is being conducted to determine what alternative method, if any, should be implemented to remediate the site. Currently, *in situ* and excavation techniques are being considered.

TREATMENT SUMMARY: *Ex situ* treatment, pile, forced air biological treatment (FABT). Aerobic conditions, indigenous organisms. The forced air biological treatment (FABT) consists of a compost pile with slotted pipes to pull the air through. This gives aeration and reverse control of vapors.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with tars from charcoal production (PAHs, phenols). Arsenic, copper, lead, mercury are also present.

(26) Hentchells, Traverse City, MI, leaking underground storage tank facility

PROCESS 1 STATUS: Full-scale remediation is being conducted. Pilot-scale studies were completed 08/93. Started 06/93. Isolated "hot spots" are currently being treated with air sparge/soil vapor extraction.

TREATMENT SUMMARY: *In situ* treatment, air sparging. Oxygen source. Aerobic conditions, indigenous organisms. Nonbiological technologies: vacuum extraction. Air sparging with soil vapor extraction. Oxygen is the only nutrient currently being added through sparging.

MEDIA AND CONTAMINANTS: Ground water contaminated with PAHs

PROCESS 2 STATUS: Full-scale remediation was completed 03/89. Started 09/85. Iron-forming bacteria clogged the carbon system. Site is pursuing final cleanup of residue at leading edge of plume and needs soil verification.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation, *in situ* soil bioremediation (*in situ* land treatment). Nutrient addition [soils, (mono- and di-sodium phosphate, ammonium choride), water, (mono- and di-sodium phosphate, ammonium chloride)]. Aerobic conditions, indigenous organisms. Treatment is closed-loop *in situ* bioremediation, in which microbial growth is enhanced through the addition of ammonium chloride, monosodium phosphate, disodium phosphate, and oxygen to ground water and soils.

MEDIA AND CONTAMINANTS: Soil contaminted with BTEX, PAHs. Ground water contaminated with BTEX

(27) Kincheloe Former Air Force Base, Kinross County, MI, fire training pit

STATUS Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies are planned. Pilot-scale studies are being conducted. Expected completion 09/94. Total expected cost: $190K. Soil at site contains low concentrations of TCE, which will be removed by soil vapor extraction. Lab-scale tests will be performed only if (a) bio-oxidation rate is much lower than expected during pilot trials and (b) regulatory agency requests them. No date for lab-scale tests is scheduled due to provisional nature of tests. A contract has been awarded for the pilot-scale studies to Engineering-Science, Inc. Full-scale remediation will depend on results of pilot trials.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Oxygen source, nutrient addition (nitrogen and phosphorous may be used depending on initial test results), additional moisture may be used depending on initial test results. Aerobic conditions, indigenous organisms. Nonbiological technologies: vacuum extraction. Process will include one vent well, screened to 55 feet (10 ft above water table), and 6 monitoring points, each having probes at 20, 30, and 50 feet below surface. If vacuum extraction is used (as it likely will be for TCE), the same blower and vent well will be used, but air transport will be at greater rate than for bioventing.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with BTEX, benzene, ethylbenzene, toluene, xylene. Chromium and lead are also present.

(28) Michigan Air National Guard, Battle Creek, MI, fire department training area

STATUS: Full-scale remediation is planned. Currently in design. Remediation expected completion 09/94. Pilot-scale studies were completed 09/93. Started 09/92. Incurred costs: capital, \$3,000; O&M, \$48. Total expected cost: O&M, \$1,268. Cost per year: O&M, \$436.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms. System consists of (1) a 1-hp regenerative blower capable of injecting 50 standard cubic feet per minute (scfm) at 2 psi; (2) a 30-ft, 4-in. diameter, PVC injection well; and (3) three monitoring wells with monitoring points at 8, 17, and 27 ft below the surface. System is run continuously with testing conducted twice a year at monitoring wells to determine contaminant levels.

MEDIA AND CONTAMINANTS: Vadose soil contaminted with BTEX. Heavy metals are also present.

(29) Organic Chemical, Grandville, MI, inactive refinery, more recently solvent recycler

STATUS Laboratory-scale studies are planned. Review of dioxin data has revealed that soil will be handled by EPA in Cincinnati. Site is waiting for the feasibility study to do remediation on the TCE and toluene and is working on an additional plan for oil. Ground water pump and treat began in December 1993.

TREATMENT SUMMARY: Bioremediation treatment not yet established. Nonbiological technologies: levels of organics are so high at the site that bioremediation is not practical until the levels are lowered. Ground water pump and treat with an air stripper and GAC is being used as an interim measure.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with BTEX. Ground water contaminated with BTEX lube oil, TCE, toluene

(30) Saginaw Bay Confined Disposal Facility, Bay City, MI

PROCESS 1 STATUS: Full-scale bioremediation is not planned. Pilot-scale studies are planned. Expected completion 04/96. Incurred cost: capital, \$3,000. Total expected costs: capital, \$3,000; O&M, \$15K. Costs per year: O&M, \$5,000. Contaminated fines from a hydrocyclone washing process will be disposed of in a 30-ft diameter tank located on a structure that is permitted to receive contaminated dredged material. The fines will be tilled periodically. The effects of weather on PCB degradation also will be monitored.

TREATMENT SUMMARY: *In situ* treatment, periodic tilling. Aerobic and anaerobic conditions, indigenous organisms. Nonbiological technologies: soil washing. Fines residue from hydrocyclone washing is applied in a thin layer (5 to 10 inches) to geotextile-covered land.

MEDIA AND CONTAMINANTS: Sediments contaminated with PCBs. Cadmium, chromium, copper, lead, mercury, nickel, zinc are also present.

PROCESS 2 STATUS: Full-scale bioremediation is not planned. Pilot-scale studies are planned. Expected completion 04/96. Incurred cost: capital, \$3,000. Total expected costs: capital, \$3,000; O&M, \$15K. Costs per year: O&M, \$5,000. Contaminated fines from a hydrocyclone washing process will be disposed of in a 30-ft diameter tank located on a structure that is permitted to receive contaminated dredged material. The fines will undergo a devegetation process. The effects of weather on PCB degradation also will be monitored.

TREATMENT SUMMARY: *In situ* treatment, devegetation. Aerobic and anaerobic conditions, indigenous organisms. Nonbiological technologies: soil washing. Fines residue from hydrocyclone washing is applied in a thin layer (5 to 10 inches) on geotextile-covered land.

MEDIA AND CONTAMINANTS: Sediments contaminated with PCBs. Cadmium, chromium, copper, lead, mercury, nickel, zinc are also present

PROCESS 3 STATUS: Full-scale bioremediation is not planned. Pilot-scale studies are planned. Expected completion 04/96. Incurred cost: capital, $3,000. Total expected costs: capital, $3,000; O&M, $15K. Costs per year: O&M, $5,000. Contaminated fines from a hydrocyclone washing process will be placed in a 30-ft diameter tank located on a structure that is permitted to receive contaminated dredged material. The effects of weather on PCB concentrations will be monitored, but no action will be taken to stimulate PCB degradation.

TREATMENT SUMMARY: *In situ* treatment, no active remediation. Aerobic and anaerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Sediments contaminated wtih PCBs. Cadmium, chromium, copper, lead, mercury, nickel, zinc are also present.

(31) Warner Lambert Company--Parke-Davis, Holland, MI

STATUS: Laboratory-scale and pilot-scale studies are planned.

TREATMENT SUMMARY: *Ex situ* treatment, fixed film. Aerobic conditions. Nonbiological technologies: air stripping and steam stripping. Fixed-film biological treatment, steam stripping, and air stripping.

MEDIA AND CONTAMINANTS: Soil and ground water contaminated with petroleum, solvents. Arsenic, chloride, zinc are also present.

(32) West K&L Avenue Landfill, Kalamazoo, MI, municipal landfill

PROCESS 1 STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale and pilot-scale studies are being conducted. Total expected cost: $16M. Laboratory-scale microcosms and pilot-scale lysimeter systems are being used to assess the biodegradative capacity of the aquifer and landfill material. Potential problems include treatment of vinyl chloride and handling of water after treatment. Discharge to POTW would be possible only with the installation of 3 miles of sewer line, and no surface water discharge is possible, so treated ground water must be reinjected.

TREATMENT SUMMARY: *Ex situ* treatment, fixed film, batch flow. Aerobic conditions. Nonbiological technologies: precipitation of metals, a carbon filter for the vinyl chloride, and landfill capping. Aerobic attached growth process. Other technologies: depending on results of ground water samples during the pump test, precipitation of metals, and a carbon filter for the vinyl chloride may need to be. Treated water will need to be reinjected, so proper injection and monitoring wells will need to be installed.

MEDIA AND CONTAMINANTS: Ground water contaminated with acetone, benzene, 1,2-DCA, TCE, 1,1-DCA, ethylbenzene, toluene, trans-1,2-DCE, vinyl chloride, xylene. Metals may be present

PROCESS 2 STATUS: Full-scale remediation is planned. Expected start 12/98. Laboratory-scale studies are being conducted. Expected completion 09/94. Pilot-scale studies are planned. Expected completion 06/97. Regulatory obstacles: ROD for the site will need to be amended as will the consent decree and SOW if remedy changed based on bioremediation field study.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. Aerobic and anaerobic conditions, indigenous organisms. Treat ground water *in situ* and pump and reinject it into landfill waste to help decompose waste within the landfill. Reinjection of leachate into landfill could cause plume to expand on all sides of the landfill.

MEDIA AND CONTAMINANTS: Ground water contaminated with 1,1-DCA, 1,2-DCA, acetone, benzene, ethylbenzene, TCE, toluene, trans-1,2-DCE, vinyl chloride, xylene. Landfill contents contain unbiodegradable materials

(33) Joslyn MFG, Brooklyn Center, MN, inactive wood preserving site

STATUS: Full-scale remediation has been underway since 08/89. Expected completion 08/95. Laboratory-scale studies have been completed. Due to extreme rainfall in May 1992, part of the land treatment unit was under water. Flooding has delayed treatment of lift 2 soil. Lift 3

(TL3) soils were applied to LTU in fall 1992. Cool wet weather slowed treatment of TL3. If treatment goals are met in 1994, the fourth and final soil lift (TL4) will be applied.

TREATMENT SUMMARY: *Ex situ* land treatment. Nutrient addition (inorganic nitrogen and phosphorous). Aerobic conditions, indigenous organisms. Nonbiological technologies: ground water pump-out system with nonbiological treatment. This is a 10-acre land treatment unit. Approximately 18 in. of contaminated soil is filled daily in each lift. Nutrients, water, and microbes are added as needed.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with PAHs, PCP

(34) MacGillis and Gibbs Company Site, New Brighton, MN, active wood preserving site

STATUS: Full-scale remediation is planned. Currently in design. Expected start 11/95. Pilot-scale studies were completed 09/89. Started 07/89. Total expected cost: capital, $1.6M. Cost per year: O&M, $330K. A pilot-scale bioremediation system was tested on site under the SITE program. The results are in a report dated September 1991 (EPA/540/A5-91/001).

TREATMENT SUMMARY: *Ex situ* treatment, fixed film, plug flow. Aerobic conditions, indigenous organisms. Nonbiological technologies: soil washing and soil incineration are under consideration. Treatment is an aerobic attached growth process in a fixed-film reactor.

MEDIA AND CONTAMINANTS: Ground water contaminated with PAHs, PCP. Arsenic, chromium also present.

(35) Allied Chemical, Ironton, OH, former coke oven facility

PROCESS 1 STATUS: Full-scale remediation is planned. Currently in design. Laboratory-scale and pilot-scale studies have been completed.

TREATMENT SUMMARY: *Ex situ* treatment, reactor used to grow microorganisms where a magnetic field is applied, then circulated to two engineered cells. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Sediments contaminated with coal tar organics (PAHs). Arsenic is also present.

PROCESS 2 STATUS: Full-scale remediation is planned. Currently in design. Expected start 06/95. Laboratory-scale studies were completed 09/92. Pilot-scale studies have been completed. Concentrations of contaminants are highly variable, making confirmation of cleanup difficult.

TREATMENT SUMMARY: *In situ* treatment, *in situ* sediment bioremediation. Oxygen source, nutrient addition. Aerobic conditions, indigenous organisms. Nonbiological technologies: incineration with onsite reuse of waste heat; pump and treat for ground water. Approximately 460,000 cubic yards are being treated by *in situ* bioremediation. Infiltration and collection trenches are used to distribute O2 and nutrients.

MEDIA AND CONTAMINANTS: Sediments contaminated with coal tar organics (PAHs). Arsenic is also present.

PROCESS 3 STATUS: Full-scale remediation is planned. Currently in design. Expected start 06/95. Laboratory-scale and pilot-scale studies have been completed.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Nonbiological technologies: incineration with reuse of onsite waste heat; pump and treat for ground water. Landfarming on a prepared 2-acre pad. Approximately 30,000 cubic yards will be treated. After 4 years, process will be compared to magnetically enchanced process to see which is more effective. Water spray system used to distribute water and nutrients. Tilling is required.

MEDIA AND CONTAMINANTS: Sediments contaminated with coal tar organics (PAHs). Arsenic is also present.

(36) Aristech Chemical, Haverhill, OH, wastwater ditches, tanks and impoundments

PROCESS 1 STATUS: Full-scale remediation has been underway since 07/94. Laboratory-scale studies were completed 06/94. Started 05/94. Pilot-scale studies have been completed.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Oxygen source, nutrient addition. Aerobic conditions, indigenous organisms. Nonbiological technologies: vacuum extraction, thermal desorption. Bioventing allows for the introduction of oxygen and nutrients into the soil. Vacuum extraction and thermal desorption are performed to remove the contaminants from the medium.

MEDIA AND CONTAMINANTS: Vadose and saturated soil contaminated with phenol. Arsenic, barium are also present.

PROCESS 2 STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies have been completed. Soil moisture and temperature were the most difficult factors to control. The land treatment process also required constant aeration to be effective. Preliminary studies were done to determine what remediation method would be the most effective process in treating the contaminated site. Land treatment had been considered but has since been determined to be less effective than bioventing.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Nutrient addition (nitrogen-phosphorus slurry). Aerobic conditions, exogenous and indigenous organisms. A bulldozer was used to aerate the ground to a depth of 4 to 5 feet for the aspiration of microbial components. Indigenous and exogenous (Munox 512) bacteria were tilled into the soil, and the land was continually rotated. Although a confinement technology does not exist at this site, the goal was to reduce concentrations of contaminants in the soil so as to minimize ground water contamination.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with phenol. Arsenic is also present.

(37) BP Oil Company, Lima, OH, inactive land farm that handled hazardous waste until 1990

STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies were completed 11/88. Land treatment permit was denied. Application of oily sludge took place in November 1990. Site is working to achieve risk levels of 0.000001 or 0.00000001 before closing, which will determine the land's final use. Facility is waiting for approval of the closure plan it submitted in November 1992. In addition, assessments are being made of moving from a residential risk-based plan to an industrial risk-based plan.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Nutrient addition (anhydrous ammonia). Aerobic conditions, indigenous organisms. Nutrients are applied to the contaminated areas in order to maintain the nitrogen levels for the microorganisms that would eventually degrade the contaminants.

MEDIA AND CONTAMINANTS: Soil contaminated with BAP, 1-methylchrysene, 1-methylnaphthalene, benzo(a)anthracene, chrysene. Barium, cadmium, chromium (III), chromium (VI), lead, nickel, zinc are also present.

(38) Union Carbide—Marietta Facility, Marietta, OH, old chemical plant

PROCESS 1 STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies were completed 07/93. A treatability study has been completed. Site is in proposed plan/ROD stage.

TREATMENT SUMMARY: *Ex situ* treatment, activated sludge, completely mixed flow. Aerobic and anaerobic conditions, exogenous and indigenous organisms. Influent is mixed with biological culture under aerobic conditions in aeration tank, then goes through clarifier which separates out liquid. The biomass is recycled back into tank; remaining biomass is dewatered.

MEDIA AND CONTAMINANTS: Soil contaminated with dioxin, dichlorinated biphenyls, monochlorinated biphenyls, PCBs, VOCs. Ground water contaminated with dioxin, dichlorinated

biphenyls, benzene, chlorobenzene, monochlorinated biphenyls, PCBs, phenol, VOCs. Aluminum, manganese are also present.

PROCESS 2 STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies were completed 07/93. A treatability study has been completed. Site is in proposed plan/ROD stage.

TREATMENT SUMMARY: *Ex situ* treatment, fluidized bed, completely mixed flow. Aerobic and anaerobic conditions, exogenous and indigenous organisms. Nonbiological technologies: GAC. Anaerobic or aerobic process in which biomass growth occurs on an inert (sand) or active (activated carbon resined material) fluidized support media that has a high surface area.

MEDIA AND CONTAMINANTS: Ground water contaminated with benzene, chlorobenzene, phenol. Aluminum, manganese are also present.

PROCESS 3 STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies were completed 07/93. A treatability study has been completed. Site is in proposed plan/ROD stage.

TREATMENT SUMMARY: *Ex situ* treatment, aerated lagoon. Aerobic lagoon. Flow-through activated sludge system without solids recycling. Oxygen is maintained only in upper liquid layers.

MEDIA AND CONTAMINANTS: Ground water contaminated with benzene, chlorobenzene, phenol. Aluminum, manganese are also present.

PROCESS 4 STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies were completed 07/93. A treatability study has been completed. Site is in proposed plan/ROD stage.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. Oxygen source, nutrient addition.

MEDIA AND CONTAMINANTS: Ground water contaminated with benzene, chlorobenzene, phenol. Aluminum, manganese are also present.

PROCESS 5 STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies were completed 07/93. A treatability study has been completed. Site is in proposed plan/ROD stage.

TREATMENT SUMMARY: *In situ* treatment, trickling filters. Treatment consists of permeable media (plastic packing or stones) to which microorganisms attach and grow. Wastewater is distributed over top of media bed by movable, rotary distribution system.

MEDIA AND CONTAMINANTS: Ground water contaminated with benzene, chlorobenzene, phenol. Aluminum, manganese are also present.

(39) Onalaska Municipal Landfill, LaCrosse County, WI, closed municipal landfill

STATUS: Full-scale remediation has been underway since 05/94. Expected completion 09/96. Laboratory-scale studies were completed 03/92. Total expected costs: capital, $400K; O&M, $20K. Soils inside the landfill have yet to be addressed. Methane in the landfill might pose a problem.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms. Treatment involves bioventing (29 air injection wells connected to air compressor) with added moisture and nutrients, and ground water pump and treat. Three out of eleven acres are under bioremediation. Floating product layer (on ground water) - extraction wells for pump and treat will prevent migration.

MEDIA AND CONTAMINANTS: Saturated soil contaminated with TCE. Vadose and saturated soil contaminated with BTEX, naphthalene,TPHs

(40) French Limited, Crosby, TX

STATUS: Predesign. This is the first full-scale application of *in situ*, slurry-phase bioremediation to a Superfund site cleanup.

TREATMENT SUMMARY: *In situ* treatment, air sparging, pure oxygen dissolution system. Oxygen source, nutrient addition (for soil, water, and sediments). Aerobic conditions, indigenous

organisms. Water is pumped from the treatment area and pressurized to between 2 and 4 atmospheres. Pure oxygen then is injected into the water, and the water passes through a pipeline contactor, in which almost 60 percent of the oxygen dissolves. The oxygen/water mixture is reinjected through an eductor, which performs two functions (1) produces a fine bubble dispersion in the treatment area, and (2) ingests unoxygenated water from the treatment area, mixes it with oxygenated water, and discharges the mixture back into the treatment area.

MEDIA AND CONTAMINANTS: Sediments, soil, and sludge contaminated with BAP, benzene, PCBs, VOCs. Ground water with unspecified hazardous contaminants.

(41) Kelly Air Force Base, San Antonio, TX

STATUS: Full-scale remediation has been underway since 02/93. Expected completion 09/94. Bioventing is to be used only within S-4 area of Kelly AFB on soils with fuel-related contamination.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Aerobic conditions, indigenous organisms. Nonbiological technologies: pump and treat for ground water. The proposed treatment consists of an engineered system to increase the microbial biodegradation of fuel hydrocarbons in the unsaturated zone using forced air as the oxygen source. This process not only provides oxygen, it also strips volatile compounds as soil vapor is extracted with the use of a blower.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with benzene, BTEX jet fuel, ethylbenzene, PCE, DCE, TCE, toluene, vinyl chloride, xylene.

(42) North Cavalcade Street, Houston, TX, inactive wood preserving site

STATUS: Full-scale remediation is planned. Currently in design. Pilot-scale studies were completed 10/92. Started 06/92. Total expected cost: $4M.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Treatment process is under design.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with benzene, PAHs

(43) Sheridan Disposal Services, Hempstead, TX, former commercial waste dispos al facility

STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies have been completed. Pilot-scale studies were completed 12/91. Started 04/91. Total expected cost: $28M. Pilot study was completed and the report finalized in August 1993. PCB levels are used as indicators of levels of other organics.

TREATMENT SUMMARY: *Ex situ* treatment, slurry reactor, completely mixed flow. Aerobic conditions. Nonbiological technologies: stabilization of residues.

MEDIA AND CONTAMINANTS: Sludge, soil, and surface water contaminated with benzene, ethylbenzene, PCBs, phenol, toluene

(44) Fairfield Coal & Gas, Fairfield, IA, discontinued coal gas production facility

STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies have been completed. Pilot-scale studies were completed 01/93. Started 12/91. Incurred cost: O&M, $150K. Total expected costs: capital, $300K; O&M, $150K. Costs per year: O&M, $150K. Future problems due to poor transmissivity of the aquifer are possible. Hydrogeologic conditions were determined to be prohibitive to bioremediation. Pilot study confirmed this.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation, injection and extraction wells. Hydrogen peroxide, nutrient addition [water, (nitrate)]. Aerobic conditions, indigenous organisms. Ground water treatment uses *in situ* bioremediation in the subsurface via injection wells. In addition, ground water is pumped and treated by carbon adsorption. Injection wells supply nutrients and extraction wells pull ground water through the treatment area. Soil is undergoing thermal treatment.

MEDIA AND CONTAMINANTS: Saturated soil and ground water contaminated with benzene, ethylbenzene, PAHs, toluene, xylene

(45) Sioux City Pilot Study, Sioux City, IA, bioremediation experimental station

STATUS: Pilot-scale studies were completed 10/91. Started 08/91. Incurred cost: capital, $250K. Total expected cost: capital, $10M. Problems included high soil moisture, a large area of operation, low temperatures, and other climatic obstacles.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic and anaerobic conditions, exogenous and indigenous organisms. Nonbiological technologies: chemical treatment. Contaminated soil goes through a chemical addition as a pretreatment and then as a cotreatment. Microbial cultures are obtained from site enrichment and cultured stock. The process involves both aerobic and anaerobic phases.

MEDIA AND CONTAMINANTS: Soil contaminated with BTEX lube oil, PAHs. Cyanide is also present.

(46) Vogel Paint & Wax, Maurice, IA, inactive industrial dump for paint manufacturing operations

STATUS: Full-scale remediation has been underway since 10/91. Total expected cost: $2M. Volatilization control/air monitoring are being evaluated.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Nonbiological technologies: air stripping of ground water, product recovery. Fertilizer is added to a land treatment unit. An 18-in. layer of contaminated soil is placed in a 1-acre treatment cell. Nutrients are added to stimulate aerobic degradation, and the soil is tilled.

MEDIA AND CONTAMINANTS: Soil contaminated with benzene, ethylbenzene, MEK, toluene, xylene. Lead, mercury are also present.

(47) Amoco Refinery, Sugar Creek, MO, RCRA land treatment facility to treat oil refinery sludges

PROCESS 1 STATUS: Full-scale remediation has been underway since 06/94. Laboratory-scale and pilot-scale studies have been completed. There have been material handling problems such as mixing sludge for uniformity and providing enough oxygen without cooling the pond below an effective temperature.

TREATMENT SUMMARY: *Ex situ* treatment, aerated lagoon, pile. Aerobic conditions, indigenous organisms. Nonbiological technologies: thermal desorption. Contaminated material is treated in an aerated lagoon for 90 days under ambient conditions; nutrients are added, and pH is controlled. Biopile augments the aerated lagoon process, and thermal desorption is being proposed to augment the combined biological process. Potential migration from a portion of the treatment unit. Lining of the LSR is planned during the fall and winter of 1994.

MEDIA AND CONTAMINANTS: Soil contaminated with phenanthrene, pyrene, naphthalene, toluene, xylene.

PROCESS 2 STATUS: Full-scale remediation has been underway since 01/91.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Nonbiological technologies: thermal desorption. Contaminated material is treated in a land farm, where it is tilled to aerate and moisture is controlled.

MEDIA AND CONTAMINANTS: Soil contaminated with phenanthrene, pyrene, naphthalene, toluene, xylene

(48) Conservation Chemical, Kansas City, MO, pre-RCRA, commercial treatment and disposal operation for industrial wastes

STATUS: Full-scale remediation has been underway since 01/90. Laboratory-scale studies were completed 01/89. Incurred cost: capital, $110K. Cost per year: O&M, $25K.

TREATMENT SUMMARY: *Ex situ* treatment, fixed film, completely mixed flow. Aerobic conditions, exogenous organisms. Nonbiological technologies: carbon adsorption, lime precipitation, and sulfide precipitation in series.
This process is an aerobic attached-growth process in series with a fixed-film bioreactor.

MEDIA AND CONTAMINANTS: Ground water contaminated with semivolatiles, phenols, VOCs. Cyanide complexes, nickel, zinc are also present.

(49) International Paper, Joplin, MO, active wood preserving site

STATUS: Full-scale remediation has been underway since 05/94. Laboratory-scale studies were completed 01/90. Started 01/88. Total expected cost: $9M. Bioremediation initially failed at this site due to lack of temperature and moisture control; the units were flooded, blocking oxygen transfer. Basins were covered (10+ acres under each of four roofs) to control moisture and temperature, and bioremediation has started up again. Unable at this time to say whether this has worked. Land disposal restrictions limit cleanup options.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Nonbiological technologies: chemical treatment, soil washing proposed but restricted by land disposal restrictions. Beds of soil are bermed to control runon and runoff and roofed to allow moisture control. Soils will then be exposed to indigenous microorganisms for 2 years. If soils don't meet standards at the end of 2 years, then the lift will be removed and treated off site.

MEDIA AND CONTAMINANTS: Soil contaminated with creosote, PAHs, PCP

(50) Offutt Air Force Base, Bellevue, NE, leaking underground storage tanks and plumbing

PROCESS 1 STATUS: Full-scale remediation has been underway since 10/93. Expected completion 10/95. Pilot-scale studies have been underway since 08/92. Problems encountered with bioventing: high water table due to rains, blower motor failure.

TREATMENT SUMMARY: *In situ* treatment, bioventing. Oxygen source. Aerobic conditions, indigenous organisms. Air is drawn through an air filter into a blower, which injects air to the soil through a vent well. The system includes temperature and pressure gauges and a flow control valve. Three monitoring points are typically used at each vent well to monitor the performance of the bioventing system. The air injected into the contaminated soil enhances the biodegradation of the contamination by providing oxygen to the indigenous micro-organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with benzene, ethylbenzene, TPHs, xylene. Arsenic, barium, lead, zinc are also present.

PROCESS 2 STATUS: Full-scale remediation is planned. Laboratory-scale studies have been completed. Pilot-scale studies are planned. Expected completion 08/95. Total expected cost: $2.5M. Getting hydrogen peroxide to all parts of shallow aquifer being treated.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. Hydrogen peroxide. Aerobic conditions, indigenous organisms. Aerobic TCE bioremediation is performed by the cometabolism process in the shallow part of the aquifer. This includes injection trenches and extraction drains. This will be combined with pump and treat from the intermediate part of the aquifer. Partial reinjection of extracted ground water is planned. The rest will be treated by a GAC unit (if necessary) before disposal to the POTW. Hydrogen peroxide will be injected for an oxygen source.

MEDIA AND CONTAMINANTS: Ground water contaminated with VOCs

(51) Conoco Landfarm, Billings, MT

STATUS: Full-scale remediation has been underway since 01/73. Pilot-scale studies have been completed. Conoco Billings Landfarm is seeking a No Migration Variance. The facility maintains a Montana Hazardous Waste Permit (MTHWP-88-02).

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Nonbiological technologies: chemical adsorption, ion exchange, precipitation. The Conoco Billings LTU is designed to degrade or immobilize hazardous waste constituents through the controlled application of wash to the soil zone. It relies on aerobic microbial decomposition and chemical adsorption, ion exchange, and precipitation.

MEDIA AND CONTAMINANTS: Sludge contaminated with K048 organics, K048 metals, K051 metals, K051 organics. Soil contaminated with petroleum.

(52) Exxon Landfarm, Billings, MT

STATUS: Full-scale remediation has been underway since 01/80. Pilot-scale studies have been completed. Exxon Landfarm (Billings) has obtained a No Migration Variance. The facility maintains a Montana Hazardous Waste Permit (MTHWP-88-01).

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Nonbiological technologies: chemical adsorption, ion exchange, precipitation. The Exxon Billings LTU is designed to degrade or immobilize hazardous waste constituents through controlled application of wash to the soil zone. It relies on aerobic microbial decomposition and chemical adsorption, ion exchange, and precipitation.

MEDIA AND CONTAMINANTS: Sludge contaminated with K049 organics, K049 metals, K050 metals, K050 organics, K051 metals, K051 organics.

(53) Geraldine Airport, Geraldine, MT, airfield contaminated by storing and loading of pesticides

STATUS: Full-scale bioremediation is not planned. No longer being considered due to failure of related pilot-scale treatability studies to substantially reduce pesticide levels.

TREATMENT SUMMARY: Aerobic and anaerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with 2,4-D, aldrin, chlordane, 4,4'-DDE, 4,4'-DDD, 4,4'-DDT, á-BHC, dieldrin, endrin, toxaphene

(54) Idaho Pole Company, Bozeman, MT, active utility pole treatment site

PROCESS 1 STATUS: Full-scale remediation is planned. Currently in predesign. Total expected costs: capital, $900K; O&M, $130K.

TREATMENT SUMMARY: *Ex situ* land treatment. Oxygen source, nutrient addition. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose and saturated soil contaminated with fluoranthene, BAP, benzo(b)fluoranthene, anthracene, benzo(g,h,i)perylene, benzo(a)anthracene, benzo(k)fluoranthene, chrysene, indeno(1,2,3-cd)pyrene, PCP, phenanthrene, pyrene

PROCESS 2 STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies are planned. Expected start 07/95, expected completion 03/96. Pilot-scale studies are planned. Expected start10/94, expected completion 03/96. Total expected costs: capital, $1.2M; O&M, $400K.

TREATMENT SUMMARY: *Ex situ* treatment, fixed film, plug flow. Aerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Sediments contaminated with fluoranthene, anthracene, BAP, benzo(a)-anthracene, benzo(b)fluoranthene, benzo(g,h,i)perylene, benzo(k)fluoranthene, chrysene, indeno(1,2,3-cd)pyrene, PCP, phenanthrene, pyrene

PROCESS 3 STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies are planned. Expected start 07/95, expected completion 03/96. Pilot-scale studies are planned. Expected start 10/94, expected completion 03/96. Total expected costs: capital, $1.2M; O&M, $400K.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. Oxygen source, nutrient addition. Aerobic conditions, indigenous organisms. Ground water is undergoing *in situ* treatment by nutrient and oxygen enhancement.

MEDIA AND CONTAMINANTS: Ground water contaminated with 2,4,6-trichlorophenol, fluoranthene, chrysene, benzo(b)fluoranthene, benzo(a)anthracene, anthracene, BAP, benzo(k)fluoranthene, fluorene, naphthalene, PCP, phenanthrene, pyrene

(55) Joliet Weed Control District, Joliet, MT, storage facility

STATUS: Full-scale bioremediation is not planned. Pilot-scale studies were completed 09/91. Pilot-scale study did not have adequate controls. No longer being considered due to high levels of dioxins and failure of related pilot-scale treatability studies to reduce pesticide levels substantially.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Aerobic and anaerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with 2,4-D, dicamba, MCPA. Arsenic is also present.

(56) Libby Ground Water Site, Libby, MT, operating lumber mill and former wood preserving facility

PROCESS 1 STATUS: Full-scale remediation is being conducted. Laboratory-scale and pilot-scale studies have been completed. Oil-water separation in bioreactor has been a problem because free product has approximately the same specific gravity as water.

TREATMENT SUMMARY: *Ex situ* treatment, fixed film, bioreactor for ground water, plug flow. Aerobic conditions, indigenous organisms. The aboveground treatment unit is designed to remove PAHs and PCP from extracted ground water. The unit consists of an equalization tank with two fixed-film bioreactors operated in series. The first reactor provides rough treatment; the second reactor polishes and reoxygenates the effluent prior to reinjection through an infiltration trench. PAH removal occurs primarily in the first reactor; PCP removal is balanced equally between the reactors.

MEDIA AND CONTAMINANTS: Ground water contaminated with PAHs, benzene, PCP

PROCESS 2 STATUS: Full-scale remediation is being conducted. Pilot-scale studies have been completed. Pyrene degradation rates in land treatment units for soils have been low, but pyrene has been removed from remediation requirements.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Land treament units (LTUs) are used for bioremediation of contaminated soil from three primary sources: the tank farm, butt dip, and waste pit areas. At the beginning of the project, contaminated soil was derocked and pretreated. After pretreatment, the contaminated soil was applied in 9-in. lifts to two adjacent, 1-acre, prepared-bed LTUs. Each LTU includes a treatment zone, liner system, and leachate collection system.

MEDIA AND CONTAMINANTS: Soil contaminated with PAHs, PCP

PROCESS 3 STATUS: Full-scale remediation is being conducted. Laboratory-scale and pilot-scale studies have been completed.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. Oxygen source, nutrient addition (potassium, tripolyphosphate, ammonium chloride). Aerobic conditions, indigenous organisms. During the period of the performance evaluation, compressed oxygen gas and inorganic nutrients were injected into the upper aquifer to stimulate the growth of contaminant-specific microbes. Oxygen was injected at a flow rate of approximately 100 gpm through three injection clusters, resulting in a concentration of approximately 100 mg/L of oxygen gas. Inorganic nutrients in the form of potassium tripolyphosphate and ammonium chloride were continuously added to achieve concentrations in the injection water of 2.4 mg/L and 1 mg/L of nitrogen and phosphorus, respectively.

MEDIA AND CONTAMINANTS: Ground water contaminates with benzene, PAHs, PCP

(57) Miles City Airport, Miles City, MT, pescticide loading and washing facility

STATUS: Full-scale bioremediation is not planned. No longer being considered due to failure of related pilot-scale treatability studies to reduce pesticide levels substantially.

TREATMENT SUMMARY: Aerobic and anaerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with 2,4-D, aldrin, chlordane, à-BHC, 4,4'-DDE, 4,4'-DDD, 4,4'-DDT, á-BHC, â-BHC, atrazine, dieldrin, Far-go, methoxychlor, parathion-e, Tordon. Saturated soil contaminated with endrin.

(58) Montana Pole, Butte, MT, inactive wood preserving site

STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale and pilot-scale studies are planned. Expected start 05/95, expected completion 11/95. Total expected costs: capital, $3M; O&M, $12M. Costs per year: O&M, $1.2M. The Montana Pole Site is in the pre-RD/RA stage and no remediation currently is taking place.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation. *Ex situ* treatment, reactor type to be determined, land treatment. Hydrogen peroxide, oxygen source, nutrient addition (nutrients not yet determined). Aerobic conditions, indigenous organisms. Nonbiological technologies: *in situ* soil flushing. Treatment process has not yet been designed.

MEDIA AND CONTAMINANTS: Sediments and ground water contaminated with PCP. Soil contaminated with PAHs, PCP. Arsenic, cadmium, chromium, copper, lead, zinc are also present.

(59) Richey Airport, Richey, MT, storage and loading of pesticides at airfield

STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies have been completed. Pilot-scale studies were completed 08/93. Started 01/93. No longer being considered due to failure of the pilot-scale treatability studies to substantially reduce pesticide levels.

TREATMENT SUMMARY: *Ex situ* treatment, reactor (type not chosen). Aerobic and anaerobic conditions, indigenous organisms.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with 2,4-D, aldrin, dicamba, chlordane, à-BHC, 4,4'-DDE, 4,4'-DDD, 4,4'-DDT, á-BHC, â-BHC, atrazine, dieldrin, endrin, Far-go, methoxychlor, parathion-e, parathion-m, Tordon

(60) Union Pacific Railroad Tie Treatment Plant, Laramie, WY, inactive tie treatment site

STATUS: Full-scale bioremediation is not planned. Laboratory-scale and pilot-scale studies have been completed. Incurred cost: $35M. Total expected cost: $35M. Fluid delivery is not uniform, so bioremediation is not uniform. Cleanup of bedrock contamination is technically impracticable. Besides bedrock contamination, there are three considerations which lead to the conclusion that it is impracticable to bioremediate the area: (1) the size of the area, (2) the cost that would be incurred, and (3) the time required to bioremediate the area.

TREATMENT SUMMARY: *In situ* treatment, *in situ* ground water bioremediation, *in situ* sediment bioremediation, *in situ* soil bioremediation (*in situ* land treatment). *Ex situ* treatment, sequencing batch reactor, land treatment. Hydrogen peroxide, nutrient addition (N:P). Aerobic conditions, indigenous organisms. Nonbiological technologies: *in situ* soil flushing, soil washing. Soil was tested using *in situ* and *ex situ* land treatment. Ground water was tested in a sequencing batch reactor. All of these technologies were tested at the pilot scale.

MEDIA AND CONTAMINANTS: Soil and ground water contaminated with creosote, PAHs, PCP

(61) Gila Indian Reservation, Bapchule, AZ, abandoned aerial pesticide applicator strip

STATUS: Full-scale remediation was completed 07/86. Started 01/84. Incurred cost: $700K. Toxaphene is very hard to break down. Materials handling was difficult.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Hydrogen peroxide, nutrient addition (alfalfa, manure). Aerobic and anaerobic conditions, indigenous organisms. Soil received amendments first under aerobic conditions, then under anaerobic conditions.

MEDIA AND CONTAMINANTS: Soil contaminated with pesticides (parathion, toxaphene)

(62) BKK Landfill, West Covina, CA

STATUS: Full-scale remediation has been underway since 01/87. Pilot-scale studies have been completed. A treatability study may be done on a mixture of landfill leachate and ground water to see if the system can treat it. Plant will be expanded. Air strippers, which exist but are not being used, might be used in the future.

TREATMENT SUMMARY: *Ex situ* treatment, fluidized bed, completely mixed flow. Aerobic conditions. Nonbiological technologies: chemical treatment, may also treat landfill liquids to see if ground water not heavily contaminated can be stripped by an air stripping process. Treatment is slurry-phase bioremediation. The bioreactor is a leachate treatment plant with a metal removal system using complexation with EDTA and floculation. PACT-carbon and biomass together combine traditional activated sludge and carbon adsorption.

MEDIA AND CONTAMINANTS: Ground water contaminated with dichloromethane, carbon tetrachloride, chloroform, benzene, 1,2-dichloropropane, phenols, TCE, toluene, vinyl chloride. Arsenic, cadmium, chromium, cyanide, lead, mercury are also present.

(63) Fort Ord Army Base, Monterey, CA, burn pit of a fire training area

STATUS Full-scale bioremediation is not planned. Pilot-scale studies were completed 05/94. Started 01/85. Ground water was not the primary medium being treated but was used as part of the pump and treat system for the soil remediation. A large pilot-scale study was performed, and the treatment that was implemented was sufficient to remediate the site to within or below risk levels.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Nutrient addition (carbon fertilizers). Aerobic conditions, indigenous organisms. Nonbiological technologies: pump and treat, carbon adsorption. The burn pit had deep soil contamination. The soil was excavated, stockpiled, and spread to shallow depths (2–3 feet). Ground water was amended with nutrients, pumped, and spread onto the soil as needed. Soil tillage also was performed on an as-needed basis.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with diesel, gasoline, toluene, xylene. Ground water contaminated with 1,2-DCE, TCE, TPHs. Chlorinated dioxins and furans are also present.

(64) Growers Air Service, Woodland, CA

STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies were completed 10/88. The study was supposed to be on a pilot scale, but it ended up on a laboratory scale. The results were inconclusive due to many QA/QC problems in the analyses. The full-scale cleanup at this site has not begun. The Regional Board has not initiated action because of staff resource limitations. Future of bioremediation at this site is unclear.

TREATMENT SUMMARY: *Ex situ* land treatment, lime addition. Anaerobic conditions. Land treatment of soil will involve excavation of contaminated soil, followed by placement in some type of large aboveground containers—fiberglass tomato gondolas work well and are a good size and shape. Lime and other amendments would be added.

Excavated soil is mixed with lime, manure, and rice hulls, then placed in tomato bins set up with a liquid drain and recovery system. The treatment may be anaerobic, achieved by flooding the bins in water. Aerobic and aerobic conditions may be alternated by draining bins and soil.

MEDIA AND CONTAMINANTS: Soil contaminated with pesticides (atrazine, Bravo, 1&2-DDT, dacthal, malathion, parathion, methyltrithion, ethion, parathion-m, paroxon, thiadine, thiadine sulfate, toxaphene, trifluralin, trithion.)

(65) Hamburg Ranch, Merced County, CA, farm air strip contaminated with pesticides

STATUS: Full-scale remediation is planned. Currently in predesign. Remediation expected completion 10/96. This site is especially difficult because of the high degree of contamination and the amount of material involved. Excavation down to 1 ppm DDT, DDD, and DDE and 5 ppm toxaphene is now taking place. Much of this material will be disposed of at a Class 1 landfill, since it is characterized as non-RCRA waste. The remainder will be bioremediated on site. Bioremediation technology has not yet been selected. White rot fungus is a possibility.

TREATMENT SUMMARY: Bioremediation treatment not yet established.

MEDIA AND CONTAMINANTS: Vadose and saturated soil contaminated with pesticides (DDD, DDE, chlorfenvinphos, DDT, endosulfan, methidathion, Monitor, Nemacur, parathion-e, parathion-m, toxaphene

(66) Hercules Incorporated, Hercules, CA, formerly used for manufacturing explosives

STATUS: Full-scale bioremediation is not planned. Pilot-scale studies were completed 01/91. Started 01/89. The pilot-scale studies were very promising, and cleanup levels were achieved fairly quickly. However, the timing for full-scale bioremediation was not favorable. There were other technical problems. Only landfarming was tried, no slurry type bioremediation.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Solid-phase bioremediation was undertaken at the pilot scale with 1 cubic yard boxes of soil.

MEDIA AND CONTAMINANTS: Soil contaminated with explosives (DNT, nitrobenzene, TNT)

(67) JASCO, Mountain View, CA

STATUS: Full-scale remediation is planned. Currently in design. Laboratory-scale studies were completed 11/91. Started 02/91. Incurred cost: $30K. Total expected costs: capital, $200K; O&M, $248K. The ROD selected an *ex situ* bioremediation process, which will combine aerobic and anaerobic treatments. The challenges at this site are (1) to minimize volatilization of contaminants during excavation, and (2) to balance the aerobic and anaerobic processes to treat the entire contaminated area. If cleanup levels are not achieved, contaminated material will be disposed of in a RCRA landfill.

TREATMENT SUMMARY: *Ex situ* treatment, *ex situ* reactor treatment, batch flow. Aerobic and anaerobic conditions. Soil will be excavated, prepared, and placed in a totally enclosed reactor vessel. In the reactor, soils will be mixed with a bulking agent and nutrients. The reactor vessel will have an air distribution system to provide oxygen to the microorganisms and extract volatile organics.

MEDIA AND CONTAMINANTS: Soil contaminated with 1,1-DCA, 1,1,1-TCA, 1,1-DCE, 1,2-DCE, acetone, benzene, chloroethane, MEK, diesel, ethylbenzene, methanol, methylene chloride, PCE, PCP, TCE, toluene, vinyl chloride, xylenes. Ground water contaminated with acetone, 1,1-DCA, 1,1-DCE, 1,2-DCA, benzene, methylene chloride, PCE, PCP, toluene, TPHs, vinyl chloride

(68) Koppers Company, Inc., Oroville, CA

STATUS: Full-scale remediation is planned. Currently in predesign. Laboratory-scale studies were completed 01/93. Pilot-scale studies are planned. Expected completion 11/94. Total expected costs: capital, $4.5M; O&M, $7.7M.

TREATMENT SUMMARY: *In situ* treatment, *in situ* soil bioremediation (*in situ* land treatment). Nutrient addition. Aerobic conditions, indigenous organisms. Nonbiological technologies: soil washing, fixation of metal-contaminated soil, ground water treatment with carbon.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with PAHs, dioxins, furans, PCP. Arsenic, chromium are also present.

(69) Montrose Chemical Corporation of California, Torrance, CA, former DDT manufacturing facility

STATUS: Full-scale bioremediation is not planned. Laboratory-scale studies were completed 03/94. Started 09/92. Inoculated fungus had trouble competing with indigenous population and did not significantly reduce DDT concentrations. Laboratory-scale studies indicated that land treatment was not an effective method of remediating the site. Test results failed to meet the proposed cleanup levels. No further bioremediation is planned, and the soil will either be capped or be taken off site for incineration.

TREATMENT SUMMARY: *Ex situ* land treatment.
Aerobic conditions, exogenous organisms. White rot fungus was inoculated into soil contaminated with DDT. The soil was then landfarmed (solid phase treatment). Removal of DDT followed. Leachate of water from the landfarming plot must be monitored for target compound.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with DDT. Benzene, chlorobenzene, chloroform are also present.

(70) Moore Aviation, Colusa, CA, commercial pesticide applicator site, air strip

STATUS: Full-scale remediation has been underway since 09/91. Laboratory-scale studies were completed 01/90. Pilot-scale studies have been completed. Total expected cost: $35K. There are some problems with QA/QC on analyses; two independent labs are giving conflicting results. Endosulfans have been particularly recalcitrant. This has not allowed the project to come to a full completion, in part because the cleanup levels are somewhat stringent.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic and anaerobic conditions, indigenous organisms. Soils were excavated, placed in aboveground shallow bins (tomato carriers), and mixed with lime, manure, and rice hulls. Bins were fitted with a drainage and recovery system and flooded to create anaerobic conditions; some bins also were drained and tilled to create aerobic conditions. Degradation was most efficient under the anaerobic regime. One bin was covered with clear plastic to create a solarization experiment, which showed real promise. All of the bins will now be emptied onto a concrete pad, with contents exposed to sunlight to try to get further degradation.

MEDIA AND CONTAMINANTS: Vadose soil contaminated with DDE, chlorpyrifos, disulfoton, 2,4-D, 2,4,5-T, atrazine, endosulfan I, endosulfan II, parathion, propazine. Bis(2-ethylhexyl)pthalate, phenols are also present.

(71) Solvent Service, San Jose, CA, solvent recycling operation

STATUS: Full-scale remediation has been underway since 01/91. Incurred cost: $399K. Total expected cost: $844K. Site had difficulty obtaining a permit for bioremediation.

TREATMENT SUMMARY: *Ex situ* treatment, fixed film, completely mixed flow. Anaerobic conditions, exogenous organisms. Nonbiological technologies: vacuum extraction, air stripper with carbon absorption unit. The ground water is pumped, then put through treatment cells where vapor condensation occurs. Water is then discharged.

MEDIA AND CONTAMINANTS: Ground water contaminated with 1,2-DCE, cis-1,2-DCE, 1,1,1-TCA, acetone, 1,1-DCE, benzene, ethylbenzene, freon 113, naphthalene, trans-1,2-DCE

(72) Poly-Carb, Wells, NV, abandoned sham waste-treater

STATUS: Full-scale remediation was completed 09/88. Started 06/87. Laboratory-scale studies were completed 05/87. Started 03/87. Incurred cost: $450K. Total expected cost: $600K.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, indigenous organisms. Nonbiological technologies: *in situ* soil flushing, *in situ* volatilization. Contaminated soil was placed in a double-lined HDPE liner and irrigated with a sprinkler. Leachate was collected on GAC, and the water recycled. Unit was tilled every 2 weeks or so.

MEDIA AND CONTAMINANTS: Soil contaminated with cresol, phenols

(73) J.H. Baxter Company, Renton, WA

STATUS: Full-scale remediation is planned. Currently in design. Remediation expected completion 10/98. Laboratory-scale studies were completed 11/92. Started 08/92. This site may not be able to meet RCRA treatability standards for land disposal. Benzo(a)pyrene appears to be the most difficult compound to degrade. Other results are very good: 40 percent to 90 percent removals on individual PAHs. Those bins experiencing drainage problems had reduced rates of bioremediation. Properly draining bins showed 90 percent reductions.

TREATMENT SUMMARY: *Ex situ* land treatment. Aerobic conditions, exogenous and indigenous organisms. Soils, sediments, and sludges will be excavated into a lined aboveground treatment bed meeting substantive RCRA requirements. Chicken manure, sawdust, indigenous microorganisms, and possibly laboratory-engineered organisms will be added to the excavated materials. Mixture will be tilled, and moisture within the bed will be controlled through recirculation of leachate.

MEDIA AND CONTAMINANTS: Sediments, sludge, vadose and saturated soil, and ground water contaminated with PAHs, PCP, TPHs

(74) Wyckoff Eagle Harbor, Puget Sound, WA, inactive wood treatment site until 1988

STATUS: Full-scale bioremediation is not planned. Site has lower TOC than expected during design and periodically experiences problems with PCP toxicity. Additional research and planning is being conducted on the site. The original treatment facility is in need of repair or replacement so that any further plans for remediation have been put on hold.

TREATMENT SUMMARY: *Ex situ* treatment, physical separation of wastes and water with activated carbon addition. Aerobic conditions. Nonbiological technologies: pump and treat for water, floating and sinking oil extraction and separation. The proposed treatment process is physical separation of wastes and water with activated carbon addition.

MEDIA AND CONTAMINANTS: Ground water contaminated with PAHs, PCP

APPENDIX B

LIST OF TECHNOLOGIES

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13. ABSTRACT *(Maximum 180 words)*
Bioremediation is a viable, cost-effective treatment for environmental contaminants. Research activities continue to uncover new bioremediation technologies, increasing the need for field-level demonstrations. The goal of this study is to identify bioremediation technologies that have demonstrated viability in laboratory or pilot studies, but require additional field demonstrations to determine the capabilities and limitations of the technology. In selecting technologies that would be of interest to the DoD, the Service-identified research and development priorities for cleanup were considered, and those contaminants amenable to bioremediation were identified. These contaminants included halogenated and non-halogenated hydrocarbons, energetics, and inorganics. Technologies that are promising at either laboratory or pilot scales and are in need of demonstrations for validation under field conditions include bioreactors for the treatment of energetics, *in situ* anaerobic/aerobic sequential treatment of chlorinated hydrocarbons, constructed wetlands, and white rot fungus. We strongly recommend the first three technologies as candidates for field-level demonstrations; the fourth we recommend less enthusiastically. Beyond our primary recommendations, we make note of two other technologies of interest: microbial mats and systems capable of assessing and monitoring bioremediation activities.

14. SUBJECT TERMS
bioremediation, microorganisms, bioreactors, white rot fungus, anaerobic bioremediation, aerobic bioremediation, constructed wetlands, energetics, hydrocarbons, halogenated hydrocarbons, inorganics, heavy metals

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